SEP 4 1923

VOLUME LVIII NUMBER 1

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

EDITED BY

GEORGE E. HALE
Mount Wilson Observatory of the Carnegie Institution of Washington

EDWIN B. FROST
Yerkes Observatory of the University of Chicago

HENRY G. GALE
Ryerson Physical Laboratory of the University of Chicago

JULY 1923

EDWARD EMERSON BARNARD - - - - - - - - - - - *Edwin B. Frost* 1

INVESTIGATIONS OF PLATE ERRORS WITH THE THERMO-ELECTRIC PHOTOMETER *Harlan True Stetson and Edwin F. Carpenter* 36

THE HYDROGEN BALMER SERIES AND THE IMPOSSIBILITY OF FURTHER CORRECTIONS TO THE QUANTIZING OF HYDROGENIC ATOMS - - - - - - - - - *Arthur E. Ruark* 46

WAVE-LENGTH STANDARDS IN THE EXTREME ULTRA-VIOLET - *J. J. Hopfield and S. W. Leifson* 59

NOTICE TO CONTRIBUTORS - - - - - - - - - - - - - - - 64

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILLINOIS, U.S.A.

THE CAMBRIDGE UNIVERSITY PRESS, London
THE MARUZEN-KABUSHIKI-KAISHA, Tokyo, Osaka, Kyoto, Fukuoka, Sendai
THE MISSION BOOK COMPANY, Shanghai

July 1923 Vol. LVIII, No. 1

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

EDITED BY

GEORGE E. HALE
Mount Wilson Observatory of the Carnegie Institution of Washington

EDWIN B. FROST
Yerkes Observatory of the University of Chicago

HENRY G. GALE
Ryerson Physical Laboratory of the University of Chicago

WITH THE COLLABORATION OF

JOSEPH S. AMES, Johns Hopkins University
ARISTARCH BELOPOLSKY, Observatoire de Poulkova
WILLIAM W. CAMPBELL, Lick Observatory
HENRY CREW, Northwestern University
CHARLES FABRY, Université de Paris
ALFRED FOWLER, Imperial College, London
CHARLES S. HASTINGS, Yale University
HEINRICH KAYSER, Universität Bonn
ALBERT A. MICHELSON, University of Chicago
HUGH F. NEWALL, Cambridge University
ERNEST F. NICHOLS, Nela Laboratory, Cleveland
ALFRED PEROT, Paris
CARL RUNGE, Universität Göttingen
HENRY N. RUSSELL, Princeton University
SIR ARTHUR SCHUSTER, Twyford
FRANK SCHLESINGER, Yale Observatory

The Astrophysical Journal is published by the University of Chicago at the University of Chicago Press, 5750 Ellis Avenue, Chicago, Illinois, during each month except February and August. ¶The subscription price is $6.00 a year; the price of single copies is 75 cents. Orders for service of less than a half-year will be charged at the single-copy rate. ¶Postage is prepaid by the publishers on all orders from the United States, Mexico, Cuba, Porto Rico, Panama Canal Zone, Republic of Panama, Dominican Republic, El Salvador, Argentina, Bolivia, Brazil, Colombia, Costa Rica, Ecuador, Guatemala, Honduras, Nicaragua, Peru, Uruguay, Hawaiian Islands, Philippine Islands, Guam, Samoan Islands, and Spain. ¶Postage is charged extra as follows: for Canada, 30 cents on annual subscriptions (total $6.30); on single copies, 3 cents (total 78 cents); for all other countries in the Postal Union, 50 cents on annual subscriptions (total $6.50), on single copies 5 cents (total 80 cents). ¶Patrons are requested to make all remittances payable to The University of Chicago Press in postal or express money orders or bank drafts.

The following are authorized to quote the prices indicated:

For the British Empire: The Cambridge University Press, Fetter Lane, London, E.C. 4. Yearly subscriptions, including postage, £1 12*s.* 6*d.* each; single copies, including postage, 4*s.* each.

For Japan and Korea: The Maruzen-Kabushiki-Kaisha, 11 to 16 Nihonbashi Tori Sanchome, Tokyo, Japan. Yearly subscriptions, including postage, Yen 13.65 each; single copies, including postage, Yen 1.68 each.

For China: The Mission Book Company, 13 North Szechuen Road, Shanghai. Yearly subscriptions, $6.00; single copies, 75 cents, or their equivalents in Chinese money. Postage extra, on yearly subscriptions 50 cents, on single copies 5 cents.

Claims for missing numbers should be made within the month following the regular month of publication The publishers expect to supply missing numbers free only when losses have been sustained in transit, and when the reserve stock will permit.

Business correspondence should be addressed to The University of Chicago Press, Chicago, Illinois.

Communications for the editors and manuscripts should be addressed to the Editors of THE ASTROPHYSICAL JOURNAL, Ryerson Laboratory, University of Chicago, Chicago, Illinois.

The cable address is "University, Chicago."

The articles in this Journal are indexed in the *International Index to Periodicals*, New York, N.Y.

Entered as second-class matter, January 17, 1895, at the Post-office at Chicago, Ill., under the Act of March 3, 1879.

Acceptance for mailing at special rate of postage provided for in Section 1103, Act of October 3, 1917, authorized on July 15, 1918.

PRINTED IN THE U.S.A.

CONTENTS

NUMBER I

PAGE

EDWARD EMERSON BARNARD. Edwin B. Frost 1

INVESTIGATIONS OF PLATE ERRORS WITH THE THERMO-ELECTRIC PHOTOMETER. Harlan True Stetson and Edwin F. Carpenter 36

THE HYDROGEN BALMER SERIES AND THE IMPOSSIBILITY OF FURTHER CORRECTIONS TO THE QUANTIZING OF HYDROGENIC ATOMS. Arthur E. Ruark 46

WAVE-LENGTH STANDARDS IN THE EXTREME ULTRA-VIOLET. J. J. Hopfield and S. W. Leifson 59

NOTICE TO CONTRIBUTORS. 64

NUMBER II

WATER-CELL TRANSMISSIONS AND PLANETARY TEMPERATURES. Donald H. Menzel 65

LIGHT-CURVE AND ORBIT OF CG CYGNI. Ch'ing-Sung Yü 75

EXCITATION STAGES IN THE OPEN ARC-LIGHT SPECTRA. B. E. Moore:

Part III. Lead, Mercury, Thallium, Magnesium 86

Part IV. Hydrogen, Air, Water-Vapor, Pressure Effect, Mixed Electrodes 104

ON THE RADIATION AND TEMPERATURE OF THE EXTERNAL PHOTOSPHERIC LAYERS. Ragnar Lundblad 113

MINOR CONTRIBUTIONS AND NOTES: NOTES ON TWO STARS HAVING VARIABLE BRIGHT LINES. Otto Struve 138

NUMBER III

ON THE DOUBLE STAR 9 ARGUS. Otto Struve 141

A DETERMINATION OF E/M FROM MEASUREMENTS OF THE ZEEMAN EFFECT. Harold D. Babcock 149

PHOTOMETRIC STUDIES OF SZ HERCULIS AND RS VULPECULAE. Raymond S. Dugan 164

THE RELATION BETWEEN THE SPECTRA AND THE SIZES OF THE ALKALI METAL ATOMS Louis A. Turner 176

WAVE-LENGTHS OF LINES IN THE SPECTRA OF STARS OF CLASS Me. Paul W. Merrill 195

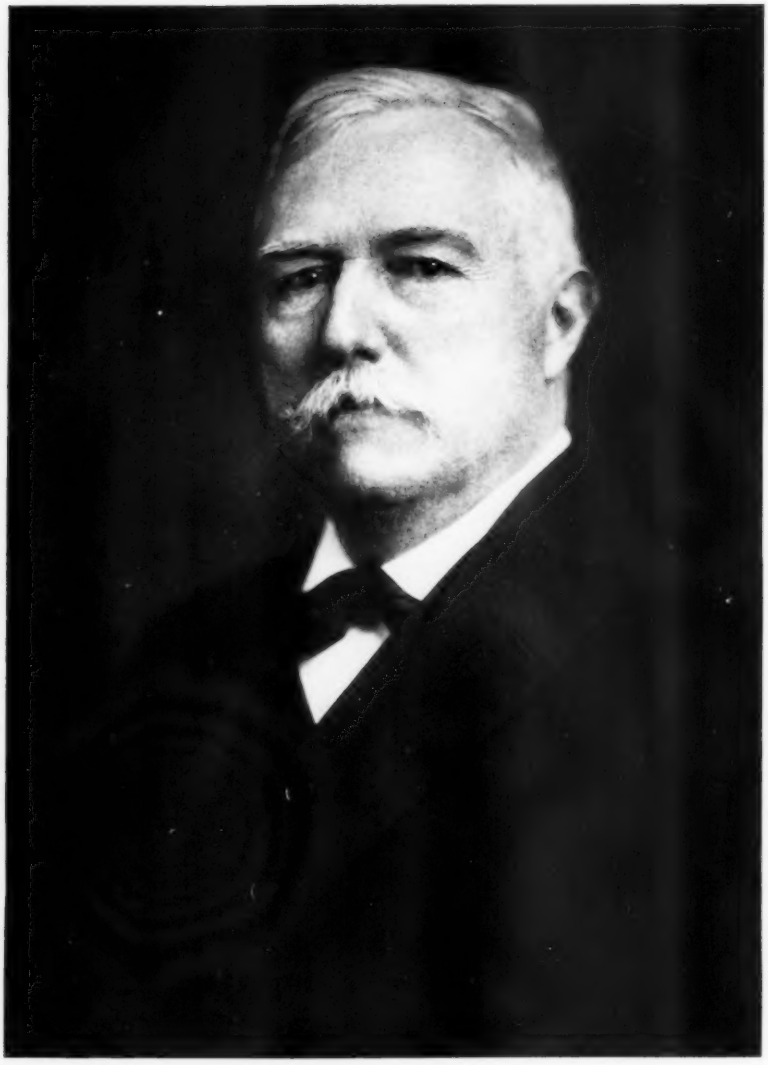
NUMBER IV

PAGE

Molecular Spectra and Half-Quanta. E. F. Barker 201
Focal Changes in Mirrors. Edison Pettit 208
The Radial Velocities of Long-Period Variable Stars. Paul W. Merrill 215
Note on the Solar Eclipse of September 10, 1923 263

NUMBER V

Spectrographic Observations of Mira Ceti, R Leonis, T Cephei, and R Serpentis. Edwin B. Frost and Frances Lowater . . 265
Arc and Spark Spectra of Aluminum, Zinc, and Carbon in the Extreme Ultra-Violet. R. O. Hutchinson 280
An Intercomparison of Temperature Scales. W. E. Forsythe . . 294
Note on the Formulation of Absorption Bands in the Near Infra-Red. W. F. Colby 303
On the Cosmic Origin of the Radioactive Substances in the Atmosphere. Hermann Bongards 307
On the Double Star 9 Argus. A Correction. Otto Struve . . 313
Erratum 313
Reviews:
Newcomb-Engelmann's Populäre Astronomie, Sechste Auflage, edited by H. Ludendorff, with the co-operation of G. Eberhard, E. Freundlich, and A. Kohlschütter (E. B. F.) 314
Notice of General Index to Vols. XXVI–L 316
Index 317



EDWARD EMERSON BARNARD

From a photograph made in 1917 by Harris and Ewing

THE
ASTROPHYSICAL JOURNAL
AN INTERNATIONAL REVIEW OF SPECTROSCOPY
AND ASTRONOMICAL PHYSICS

VOLUME LVIII JULY 1923 NUMBER 1

EDWARD EMERSON BARNARD

BY EDWIN B. FROST

Edward Emerson Barnard was born at Nashville, Tennessee, on December 16, 1857, the son of Reuben and Elizabeth Jane (Haywood) Barnard. His father had died before his birth and his mother was obliged to support herself and her two young sons. Those were hard times for poor people in that section of our country, and they were still harder after the Civil War came on, a few years later, bringing tragedy to all on the scene of conflict. The lad's memory of the flashes of artillery at the Battle of Nashville never left him. Later in his youth he survived an attack of cholera, when that plague raged beyond its accustomed habitat.

His mother was a woman of character, and did not lose her taste for culture in the struggle with poverty. The name, Emerson, given to the young son in honor of our American philosopher, was an evidence of this. She inspired the lad with a desire to know good literature, although his opportunities for any regular education in school were most meager; in fact, Edward Barnard attended the common school only two months in his life. His mother had a taste for art, also, and partially supported herself by modeling wax flowers. That she had impressed upon her son character and self-reliance was indicated by her statement that the lad, when less than nine years old, could be depended upon to do a task in which many

other boys had failed. A photographer in Nashville had on the roof of his studio a ponderous enlarging camera which had to be kept pointed at the sun. Most of the lads had lacked the patience necessary in the human substitute for a driving clock, and went to sleep at the task. Edward Barnard justified his mother's confidence; he worked in that studio, in various capacities, for seventeen years. His duties, doubtless often monotonous, were fitting him to be a pioneer in the photography of the heavens.

As a boy, he had watched with wondering eyes the starry skies above him, as he lay upon an old wagon-box in the yard; and he had, indeed, learned to know the stars, but not their names or their constellations. A young man employed in the studio, who had mechanical skill, one day picked up in the street the small objective of a broken spyglass, and, making for it a paper tube, constructed a small telescope for the young apprentice. With this, Edward Barnard studied the stars further, but still without the means of identifying them, until chance brought into his hands, somewhat later, a volume of the works of Thomas Dick, who enjoyed a considerable reputation as a writer on astronomy as well as on theology. It seems that Barnard found his first star map here, and was delighted to learn the conventional names of the objects with which he was already so familiar. Later, he put together a better instrument for which he purchased lenses of $2\frac{1}{4}$ inches aperture.

The young man was now supporting himself and his mother by his daily work in the studio, but his passion for astronomical observation had already developed. Through rigid economy he gratified this passion by the purchase, in 1876, of a 5-inch telescope, equatorially mounted, from John Byrne, of New York. The purchase price, $400, represented some two-thirds of a whole year's earnings, and thus gives sufficient evidence of his determination to acquaint himself with the science of astronomy. In 1877 the American Association for the Advancement of Science held its annual session at Nashville, and the youth of twenty, who was becoming locally well known for his zeal as a star-gazer, joined the Association. His friends persuaded him to bring his telescope and meet the president of the Association, Simon Newcomb. This distinguished astronomer, already eminent at the age of forty-two, whose researches were in

the domain of theory rather than in observation, advised young Barnard that to accomplish anything important in astronomical research he must first be well grounded in mathematics. This advice might have discouraged a less ardent seeker for knowledge of the stars, but it inspired Barnard to do just what was advised. He applied himself diligently to elementary mathematics and other common items of education which he had been obliged to neglect in his youth, and from his own slender earnings hired a tutor for some branches of his study.

In January, 1881, while still an employee at the studio, he married Miss Rhoda Calvert, who was born in Yorkshire, England, and had come to Tennessee a few years earlier with her brothers, who were artists and who also had work in connection with the studio. His marriage greatly influenced his subsequent career, as his wife most unselfishly encouraged and helped him in his efforts to obtain a better education and to overcome some cultural deficiencies of which he was conscious. She proved a true helpmeet in every way, caring for the household in a most prudent manner and taking over all responsibility for his now invalid mother. This made it possible for him to improve every opportunity that presented itself for his advancement.

On May 12, 1881, Barnard discovered his first comet in the morning sky near Alpha Pegasi. He found it again on the next night, but could not afterward locate it, and inasmuch as he did not send out any announcement to the astronomical world, and it was not seen by any other astronomer, this comet was never assigned a place in the formal records of astronomy—no number was given it and it was not counted by Mr. Barnard himself. Of course, from what was later known of his reliability and skill as an observer, there could be no question as to the certainty of his observation, but at that time he was unknown among astronomers.

This accidental discovery, however, developed his interest in the search for comets, and he began systematically to sweep the sky for them. His diligence was rewarded on the night of September 17 of the same year, when he found a comet in the constellation Virgo. He announced the discovery to Dr. Lewis Swift, so that it was observed by other astronomers and received the name, "Comet

1881 VI." Mr. H. H. Warner, who had established at Rochester, New York, the private astronomical observatory of which Dr. Swift was the director, had taken much interest in astronomy and offered a prize of $200 for each unexpected comet discovered by an American observer. The award was made to Mr. Barnard for the discovery of this comet, and it happened opportunely, for at that time the young man was building a little house for his bride and his mother, and the burden of paying notes on borrowed money as they came due was a serious one. Five times in all Barnard received this award for the discovery of a comet, and it meant to his family the possibility of owning their modest home. That dwelling is still known in Nashville as the "Comet House." Few, indeed, are the astronomers whose keen eyesight and extraordinary diligence in the quest for celestial discovery have literally provided them with a roof to sleep under. It was very little, however, that he slept under that roof when the sky was clear.

I am describing these circumstances in this detail because they may seem almost incredible to some of our contemporary European astronomers who have reached positions in our science in university or governmental observatories after passing through a very definite and uniform course of study and training. That inborn genius can find a way of achieving its ideal in America, we may call to witness our lately departed friends, Burnham and Brashear, as well as Barnard.

A year later, on September 13, 1882, the second recorded comet (1882 III) was discovered with the 5-inch telescope. A rather dramatic incident occurred a month later, October 14, of which we have a printed record in Barnard's own words. He had been searching for comets through the early part of the night and had set his alarm clock for a later hour, in order to get some much-needed rest. He says that when the alarm clock sounded he had been dreaming of discovering a wonderful field of comets, big and little, with long and short tails, in his field of view. After he awoke, he began sweeping in the neighborhood of the Great Comet of 1882, and to his astonishment saw twelve or fifteen small comets, of varied appearance, in the vicinity. He had obtained positions for seven or eight of these when the dawn came. He announced his discoveries to Dr. Swift,

but this astronomer did not distribute the information. Speaking of this omission, Mr. Barnard has said: "Whether he thought that I was trying to form a comet trust, or had suddenly gone demented, has never been clear to me." These comets were undoubtedly real, and fragments of the Great Comet. Schmidt, of Athens, reported one such object which he observed on October 8, another was observed by E. Hartwig on October 9, and still another by Brooks, of Phelps, New York, on October 21. They were never separately announced in the list of comets.

During this time, young Barnard was working in the studio by day, for a livelihood; and studying, by himself or with a tutor, on cloudy and moonlit nights. In 1880 he planned to write a booklet on Mars, and solicited subscriptions from friends in Nashville to cover the cost of publication. We have been unable to find a copy of this, which was planned to be a duodecimo; and it is doubtful whether it was ever actually printed. In 1883, we find the young amateur conducting an astronomical column in a journal known as the *Artisan*, which was published twice every month at Nashville. In the same year, friends who had perceived the genius of the young man offered him a fellowship in Vanderbilt University at Nashville, giving him an opportunity to devote his time exclusively to his studies and to make use of the 6-inch equatorial of the small observatory of the university. The stipend was only about $300, together with a house on the university campus, near the observatory, and it might have been regarded as a venturesome step for a young man with a wife and a mother dependent upon him to give up his work at the studio and endeavor to live on the sum provided. But his wife bravely counseled acceptance of the offer, and said, "We will get along somehow"; and they did. Barnard became enrolled as a special student in the school of mathematics, at the same time having the care of the observatory. Later, he received an appointment as instructor in practical astronomy, continuing his studies in mathematics, physics, and chemistry, and some of the modern languages.

The young astronomer's first trip into the outer world was made in 1884, when he attended the meeting of the American Association for the Advancement of Science at Philadelphia, visiting en route

the observatories at Cincinnati, Allegheny, Washington, Harvard, Albany, and Princeton, and seeing for the first time those cities, together with New York and Boston. Every economy had to be practiced, and he was accustomed to avoid unnecessary hotel bills by traveling in day coaches at night. His record of this trip, in daily postal cards and letters to his wife and his mother, is very humorous and interesting. He had formed, in advance, mental pictures of the prominent contemporary astronomers, and many of them turned out to be quite different from his anticipations. Thus, he had expected that Professor E. C. Pickering would be a formal and distant dignitary, as might befit a native of Boston and the director of the Harvard College Observatory. To his surprise, he found that "Professor Pickering is comparatively a young man, and strongly resembles a simple countryman. Had anyone shown him to me on the street and told me that was the famous director of the Harvard College Observatory, I should not have taken his word on oath. I should have been positive there was a mistake. However, he is the most unassuming man that you can imagine, and I admired him very much, indeed."

The meeting at Philadelphia in the section of astronomy was honored by the presence of John Couch Adams, of Cambridge, and Robert Ball, then Astronomer Royal for Ireland. To his great regret, Mr. Barnard, who was suffering from neuralgia, could not stay through the evening address of the latter, but he tells of the meeting of the section on another day, when an American astronomer (now deceased), who had specialized on the theory of the motion of the moon and who thought he had found the right basis for a correct theory, was giving a paper on his favorite topic. The situation is described by Barnard as follows:

> Now this same problem has been more or less Adams' hobby, and it was interesting to watch the twitching of his fingers during the progress of the paper. When it was finally through, and criticisms were in order, he quickly rose and in the most rapid manner proceeded to show that the gentleman was altogether in error, and went through the tedious formula with the ease of a master, and showed here and there where certain assumptions were erroneous, and where a false step had been made. It was quite a picture to see him. He has a peculiar affection, causing him, when excited, to breathe through his nose with a sound like escaping steam at almost every sentence; especially was this noticed when he used a word that began with "s."

Barnard arrived at Nashville, thoroughly worn out with his travels; but, after having received a most friendly welcome and recognition from the astronomers whom he had at last met in person, he could henceforth feel that he was one of the fraternity.

In 1887, at the age of thirty, he received the degree of Bachelor of Science. Meanwhile, he had discovered seven more comets—the last on May 12, 1887—namely: 1884 II, 1885 II, 1886 II, 1886 IX, 1886 VIII, 1887 III, 1887 IV. Of these comets, 1884 II was periodic, with a return expected every 5.4 years, but it escaped detection in subsequent years. In 1887 he published in the *Astronomische Nachrichten* a parabolic orbit for Comet 1887 III.

In 1883 he had independently discovered the Gegenschein, while sweeping the skies, and had become extraordinarily familiar with the objects in the sky which could be seen with a small telescope. He had given special attention to the planet Jupiter and was an independent discoverer of the red spot, although some months after it had been announced by C. W. Pritchett, of Glasgow, Missouri, in July, 1878. Barnard was a careful delineator of what he saw and many of his early sketches of Jupiter were published in the first volumes of the Astronomical Society of the Pacific.

In 1887 the Lick Observatory was nearing completion, and Professor E. S. Holden had been chosen director, functioning ad interim as the president of the University of California. He corresponded with Barnard, and in that summer offered him a position on the staff then in process of formation. Barnard accepted the opportunity to join this finely equipped institution, and in September he and his wife started on their interesting journey to California. They found temporary lodgings in San Francisco, until they should be able to make their home on Mount Hamilton. There were delays in the completion of the observatory, and the regents of the university were unable to make provision for the astronomers until the trustees of the Lick estate had formally turned over to them the completed observatory. Mr. Barnard, again finding himself in need of a salary which was not forthcoming, obtained work in copying legal papers in the office of a lawyer. Early in the next spring the Lick trustees invited him to come to the mountain and make an inventory of the observatory's equipment. Finally, on June 1, 1888, Director Holden was able to write, with evident relief after the try-

ing delay: "The observatory begins its active existence tonight." S. W. Burnham and J. M. Schaeberle were senior astronomers, J. E. Keeler and E. E. Barnard, juniors; and work began enthusiastically. Mr. Barnard became very warmly attached to these members of the staff. We must remember that this was his first opportunity to be regularly associated with astronomers of considerable experience, and it was of great importance to him. In turn, his associates highly appreciated Barnard's ability as an observer and his tremendous capacity for work.

The 12-inch telescope was assigned to Barnard, together with the comet-seeker, and very soon Director Holden began to make use of Barnard's technical knowledge of photography. On September 2, Barnard discovered Comet 1889 I, and in October, Comet 1888 V. He also observed their positions assiduously with the excellent equatorial and filar micrometer. He further observed nebulae and planets, and in 1889 made a notable observation of the eclipse of Japetus by the ring system of Saturn. He could see that the sunlight illuminated the satellite through the crape ring, thus indicating that the ring was quite transparent, and supporting the view that it was made up of small particles. During that year he discovered Comets 1889 II and 1889 III (which has a computed period of 128 years), but his most important work was the beginning he made during that summer in photographing the Milky Way with the Willard lens, which became a famous instrument in his hands. This was a portrait lens of 31 inches focal length, which had been used by some photographer and had received its name from the dealer who sold them in New York. This camera was strapped to the $6\frac{1}{2}$-inch equatorial, which served as a guiding telescope. Barnard's long exposures with this instrument brought out the wonderful richness of the star clouds and other features of the Milky Way as they had never before been revealed. They thrilled him and his associates with their significance and beauty, and later the entire scientific world shared in this appreciation of them.

Barnard was the first to observe the return of d'Arrest's Comet in 1890, and, in the following year, of Comets Encke and Tempel-Swift. In 1891 he discovered Comets 1891 I and 1891 IV. In 1892 he made the first discovery of a comet by photography, finding on

his plate taken on October 12, Comet 1892 V, for which a period of 6.5 years was computed, but which has never been observed at a subsequent return.

As a junior member of the staff of the Lick Observatory, Mr. Barnard did not receive a regular assignment at the 36-inch telescope, but his friend, Burnham, was always glad to check any important observation for him, or give him the opportunity of examining it with the great refractor. Professor Burnham resigned his position in June, 1892, and resumed work as clerk of the Federal Court in Chicago. Mr. Barnard had naturally been eager for an opportunity to make regular use of the great refractor, but he had been unable to secure this privilege until the first of July, 1892, when he received the coveted assignment for one night per week. On the eleventh night (September 9, 1892), he made with it his brilliant discovery of the fifth satellite of Jupiter. We quote from his own account of his observations in *Astronomy and Astrophysics*, **11**, 749, 1892:

> Friday being my night with the 36-inch telescope, after observing Mars and measuring the positions of his satellites, I began an examination of the region immediately about the planet Jupiter. At 12 o'clock as near as may be, to within a few minutes, I detected a tiny point of light closely following the planet and near the 3rd satellite which was approaching transit. I immediately suspected it was an unknown satellite and at once began measuring its position-angle and distance from the 3rd satellite. On the spur of the moment, this seemed to be the only method of securing a position of the new object, for upon bringing the slightest trace of the planet in the field the little point of light was instantly lost.
>
> I got two sets of distances and one set of position-angles, and then attempted to refer it to Jupiter but found that one of the wires of the micrometer was broken out and the other loose. Before anything could be done the object rapidly disappeared in the glare of Jupiter. From the fact that it was not left behind by the planet in its motion, I was convinced that the object was a satellite. A careful watch was kept at the preceding limb of the planet for the reappearance of the satellite, but up to daylight it could not be seen.
>
> Though positive that a new satellite had been found, extreme caution suggested that it would be better to wait for a careful verification before making any announcement.
>
> The following night with the 36-inch belonging to Professor Schaeberle, he kindly gave it up to me, and shortly before midnight the satellite was again detected rapidly leaving the planet on the following side. That morning I had

put new wires in the micrometer, and now began a series of careful measures for position. As I have said, the satellite was so small that no trace of Jupiter could be admitted into the field for reference in the measures. It was necessary, therefore, to bisect the satellite, with the planet out of the field, and then by sliding the eyepiece bring the limb of Jupiter into view and bisect it. This method did not permit any measures from the polar limbs of Jupiter. Following the satellite thus, it was seen to recede from the planet to a distance of some 36″ from the limb when it gradually became stationary. Remaining so for a while it began once more to approach the planet and rapidly disappeared in the glow near the limb. The measures, repeated as rapidly as possible, thoroughly covered the elongation, and gave the means of approximating to its period.

The following morning a telegram was sent out announcing the discovery. Subsequent observations have thoroughly confirmed the discovery.

On account of its extreme closeness to the planet it is difficult to say just what its magnitude is. Taking everything into account, I have provisionally assigned it as thirteenth magnitude. I hope to be able to settle definitely this question by observing some little star near Jupiter and then afterwards determining its magnitude when the planet has left it. Until this is settled, any estimate of the actual size of the satellite must be the merest guess, but it will probably be found to not exceed 100 miles in diameter, and perhaps less than that.

After the first few observations I inserted a piece of smoked mica in the eyepiece, and using this as an occulting bar, the measures were made with ease and accuracy. Careful measures thus made from the polar limbs for the Jovicentric latitude of the satellite show that its orbit lies sensibly in the plane of Jupiter's equator and that consequently the satellite is not a new addition to the Jovian family, since it would doubtless require ages for the orbit to be so adjusted if the object were a capture.

The reader will note from this extract the element of independence which was a characteristic of Barnard's discoveries. He perceived with a sort of intuition that this was probably a new satellite, in fact, was convinced of it, by his brief observations on the first night. His exercise of great care in making no premature announcement was also characteristic. He furthermore was quick to realize that it would be a matter of general interest whether the satellite had been newly acquired by Jupiter, and his measurements to decide this point were made a few evenings later. We also see an illustration of his readiness to adapt his observing methods to difficult circumstances, in providing a piece of smoked mica for occulting the brilliant planet. His scientific caution and ingenuity

are illustrated by his proposal that the magnitude of the object should be determined by comparison with some star of about the same magnitude, which some night would lie near the planet's position and thus afford a reliable basis for an estimate of brightness.

This first addition to the family of Jupiter, which had received careful telescopic observation for nearly three centuries, brought to Mr. Barnard instant recognition as an observer of the first class. The Lalande gold medal of the French Academy of Sciences was awarded to him a few months later for this notable astronomical feat. Professor Barnard followed this satellite with very careful micrometric measurements for many years after its discovery, seeking to improve our knowledge of its orbit, and he published 14 papers covering his observations of elongations, nearly all of them in the *Astronomical Journal*. The difficulty of observing the object was not because it was so faint, but because of the brightness of the planet. Quite good conditions of seeing were always necessary for observing it, even with the large telescope. So far as is known to the writer, the fifth satellite has never been photographed and the smallest aperture with which it has been observed is that of the 18½-inch equatorial of the Dearborn Observatory at Evanston, with which Professor G. W. Hough observed it on October 15 and November 11, 1892. The discovery of this satellite doubtless renewed interest in the search for other satellites by the use of photography, resulting in the discovery of three further, remote satellites at the Lick Observatory: VI and VII by C. D. Perrine, and IX by S.P. Nicholson; while VIII was discovered by P. J. Melotte at Greenwich.

During the later years at the Lick Observatory, Mr. Barnard gave much attention to careful measurements of the diameters of the planets, including the four largest asteroids. He made a comprehensive study of the dimensions in the Saturnian system, and measured the ellipticity of Uranus. He gave particular attention to the diameters and the appearance of the brighter satellites of Jupiter. These extensive researches were published in a series of papers in various astronomical journals, several of them appearing after he had left the Lick Observatory. He summed up his results in a paper which he published in *Popular Astronomy*, **5**, 285–302,

1897, entitled, "Micrometrical Determination of the Dimensions of the Planets and Satellites of the Solar System, Made with the 36-Inch Refractor of the Lick Observatory." This was later printed in abstract in the *Monthly Notices of the Royal Astronomical Society*, **58,** 216–218, 1898.

It was not only to the study of the Milky Way that Barnard was applying photography with distinguishing success. He studied the comets, and took a great interest in the remarkable behavior of their tails as revealed on his negatives. Swift's Comet (1892 I) was the first to show on Barnard's photographs the extraordinary changes which the tails of comets may undergo. His subsequent photographs of many comets show that these changes are characteristic of the tails of some comets, but not of others. Cloudy weather had interfered with observations of this comet during March, but the photographs taken on April 4 and 5 displayed extraordinary changes in the short interval between them. The significance and value of the photographic records of these capricious changes were instantly appreciated by Barnard, as will be seen from the following quotation from his article written some years later and appearing in the *Monthly Notices of the Royal Astronomical Society*, **59,** 355, 1899:

> This [Swift's Comet of 1892] was the first comet to show to the photographic plate the extraordinary changes to which these bodies are subject. Indeed, if it had not been for the photographic plate we should have known nothing of the extraordinary changes that occurred in this comet and several that have since appeared. . . . .
>
> For the study of the phenomena of the tails of comets, the portrait lens has shown itself most admirably suited. It has added an interest to the physical study of these bodies that did not exist previously; for the most interesting of the phenomena shown by comets must always escape the visual observer and pass unknown, without the aid of the portrait lens and the photographic plate. Unlike the planets, the comets often traverse the entire solar system. They are, therefore, our only means of exploring the regions between the planetary orbits. Instead of ponderous bodies like the planets, they are but flimsy creations of enormous dimensions. They are thus likely to be easily subject to disturbances in their forms that would produce no perceptible effect on their motions. What these influences may be we do not know; probably swarms or streams of meteors, which we know do exist in space, or possibly some other cosmical matter yet unknown. Such objects might be (and possibly have been)

revealed to us by their effect upon the form of the comet's tail as it sweeps through space.

The comet discovered by Holmes in the autumn of the same year (1892 III) was also photographed by Barnard when this round, tailless object, whose motion was almost entirely in the line of sight, was situated very near the great nebula in Andromeda. The motion of the comet among the stars was, in fact, so slight that Barnard, with an exposure of 75 minutes, obtained, on the night of November 21, 1892, a sharp picture of the Andromeda nebula, together with the comet! a circumstance which is not likely to be duplicated. Brooks's comet of the next year (1893 IV) excited Barnard's interest in a high degree by its behavior, which was quite exceptional in those early days of cometary photography. He speaks of his plates of October 21 and 22 as follows (*ibid.*, p. 358):

> There is an utter transformation of the comet in this picture. The tail is larger and brighter and very much distorted, as if it had encountered some resistance in its sweep through space. This disturbance seems to have disrupted the north-east edge of the tail. The small side tail has apparently been swept away, while the more distant portion of the main tail is streaming in a very irregular manner. The entire picture is highly suggestive of an encounter with some sort of resistance. Is it possible the tail passed through a stream of meteors such as we know exist in space? Whatever the cause may have been, the appearance of the tail utterly excludes the idea of the phenomenon being due to irregular emission of the matter from the nucleus—an explanation quite satisfactory in the case of Swift's Comet.
>
> In passing, this particular photograph seems to explain at least one of the ancient descriptions of a comet, viz., "a torch appeared in the heavens." The comet, as shown in the photograph, is sufficiently suggestive of a torch streaming irregularly in the wind.
>
> * * * *
>
> [On the next day the tail of the comet] appears a total wreck in this photograph, and is still more suggestive of a disaster. It is very badly broken, and on the south-west side hangs in irregular cloud-like masses. Near the extremity a large gap exists in the tail, as if something had gone through it from the north-east, and a large mass is torn off beyond this break and seems to be drifting independent of the comet.

For nearly thirty years these unexplained caprices of the tails of comets fascinated Professor Barnard, and whenever a new comet appeared in the sky he was filled with suppressed excitement as to its

behavior on the photographic plate. Comet Morehouse (1908 IV) was thoroughly satisfying in this respect, and he obtained no less than 350 photographs of it. He would sometimes take successive photographs of it as long as it could be followed above the horizon, before the interference of the moon or dawn.

The results of Barnard's assiduous campaign at the Lick Observatory, from 1892 to 1895, in the study of the Milky Way and comets by photography, are preserved in Volume XI of the *Publications* of the Lick Observatory. This volume did not appear until 1913—nearly twenty years after the photographs were taken—because of the difficulties which Professor Barnard found in securing satisfactory reproductions of his pictures. His studies of these photographs had been so minute that he recognized details which would have escaped anyone else, so that his standard of excellence of their reproduction became very exacting; indeed, beyond the possibility of the processes of photogravure and heliogravure. The publication of the volume had been made possible by subscriptions for the purpose which Mr. Barnard had secured from California friends of the Lick Observatory and of himself. The collotype process was employed and the reproductions are as satisfactory as could be expected by any such process. But for a number of years the responsibility of issuing this volume was a heavy one for Mr. Barnard. He became discouraged with what he regarded as the impossibility of securing adequate reproductions, and the work lapsed. He even attempted to return the money already expended, to the Lick Observatory, for distribution among the subscribing friends. He was, however, persuaded to resume and, fortunately, was able again to secure the services of the expert in collotype who had begun the work. The volume contains 129 plates, from 92 photographs of the Milky Way and 42 of comets; and it will stand as a monument to the great skill and the untiring zeal of the pioneer in his beginning in this important field of investigation.

A leave of absence was granted Mr. Barnard in the summer of 1893 to make his first trip to Europe. Mrs. Barnard accompanied him, and thus had an opportunity to visit her old home and her relatives in England. The very cordial welcome given to Barnard by his English colleagues also made this a most pleasant visit. He

then went over to the Continent and made the personal acquaintance of astronomers in France and Germany.

Mr. Barnard's residence of nearly eight years in California was full of romantic interest for him. The conditions for his work were very fine, and a clear sky was assured in advance during many months of the year. His residence on the mountain was novel to one who had always lived in a city, and the views of mountain and canyon made a strong appeal to the artistic element in his nature. The life was isolated in winter, but this was broken by visits on Saturday evenings of the winter tourists in California, and acquaintances were established—many of them lasting—with interesting people from different parts of the world. The association with his fellow-observers and their families in the little colony was congenial, and particularly close was his association with Professor Burnham, who, like himself, was an ardent and expert user of the camera. This phase of his life at the mountain was well brought out in Mr. Barnard's biographical sketch of Mr. Burnham, published in *Popular Astronomy*, **29**, 309, 1921. There was an element of the wild in the howl of the coyotes in the canyons and in the occasional deer seen around the mountain. In the gray dusk, one morning, as Mr. Barnard was nearing the door of his cottage, he saw before him the great form of a panther, or mountain lion, standing a few yards away. Each was returning from his night's work, and each silently respected the rights of the other. After a moment, the panther quietly walked on over the mountain. At another time, as Mr. Barnard was watering the flowers around the cottage, the blazing eyes and terror-stricken cries of the little dog that had been accompanying him told him that a rattlesnake had made its strike, so he dispatched the snake and rushed to apply remedies to save the life of the dog, which, as a result, survived his wound for some months.

The free and hearty cordiality of the Californians, and their appreciation and respect for the men of science on Mount Hamilton, was keenly felt; and he occasionally participated in the meetings and activities of the Camera Club and of the Bohemian Club of San Francisco, as well as with the colleagues at Berkeley. Conditions of life on the mountain were comparatively simple and at the start Mr. Barnard's salary was small; but these circumstances were much

improved toward the end of his stay, and his opportunities for the use of the great telescope were increased so that he often worked with it on two and sometimes even three nights a week. However, circumstances into which we need not enter finally led him to desire a change, and in 1895 he accepted an invitation to become a member of the staff of the Yerkes Observatory, then in process of construction as a department of the new University of Chicago. His official title was to be Professor of Practical Astronomy and Astronomer at the Yerkes Observatory, but no duties of giving instruction were involved, beyond an occasional popular lecture in the summer courses at the University. His official connection with the University began on October 1, 1895. As had happened at the Lick, there were unexpected delays in the completion of the Yerkes Observatory, so that for the greater part of a year Professor Barnard lived in Chicago near the Kenwood Observatory, the equipment for which had been presented to the University by Professor George E. Hale, for whom it had been built. This period constituted something of a gap in Mr. Barnard's observational activity, but the time was usefully employed in preparing for publication some of the results of his observations at Mount Hamilton, including the reproductions of the photographs of the Milky Way and comets made there.

In the summer of 1896, Professor and Mrs. Barnard occupied a cottage on the shore of Lake Geneva, and began the construction of the house which was to be their home for the next quarter of a century, on land which they had purchased adjacent to the grounds of the Observatory. In February, 1897, Mr. Barnard went to England to receive the gold medal of the Royal Astronomical Society, but, owing to delay of the steamer by bad weather, he unfortunately did not arrive until the day after the annual meeting of the Society. A special meeting was held on March 2, at which Professor Barnard exhibited and explained some of his most notable photographs taken at the Lick Observatory, and a dinner was given like the one prepared on the evening which he missed. As Mr. Barnard was very keen to begin work with the 40-inch, which was then expected to be ready in the spring, as well as to complete the equipment of his new home, in which he took a great interest, he

sailed for home after a stay in England of less than three weeks, and was back at Williams Bay by the middle of March.

A few weeks later the objective was brought from Cambridge by Alvan G. Clark, and was adjusted by him in its cell on the great instrument. It was first used on the night of May 21, and the tests of its performance were highly satisfactory. There were occasional opportunities during the next week, when the sky was clear, for further tests, and on the night of May 28 Professor Barnard had a narrow escape. He was observing during the latter part of that night, until daylight, and left the dome at dawn. Just before seven o'clock, as the result of faulty connection of the supporting cables, the rising floor fell, involving its almost complete destruction, but fortunately without injuring the telescope itself. Had this happened a few hours earlier, the observer could hardly have escaped death or a serious injury.

This delayed the formal opening of the Observatory until October 21, 1897, and Mr. Barnard had to exercise his patience in waiting for further use of the great refractor. As soon as it was ready for regular work, in the autumn of 1897, Professor Barnard again plunged into observing, having the great telescope at his disposal regularly for two, and often for three or four nights per week. He was, of course, interested in making some tests of the quality of the 40-inch as compared with the 36-inch telescope which he had previously used. He, therefore, observed some of the difficult double stars, such as Schaeberle's companion to Procyon, and Kappa Pegasi, and secured some elongations of the fifth satellite of Jupiter. He studied some of the variable stars in Messier 5 which had recently been discovered by Professor Bailey, finding a couple of additional variables in that cluster. He gave particular attention to the variations in brightness of Bailey's No. 33, as will be mentioned later. He also measured in the daytime the diameters of Venus and Mercury, sometimes under especially fine conditions of seeing.

He began at this time a micrometric triangulation of some of the globular star clusters, measuring in this first year the positions of 95 stars in Messier 5 and a smaller number in Messier 13, comparing

the positions of the latter with measures obtained by Scheiner at Potsdam on photographs taken in 1891. The views of astronomers as to the size of the clusters were quite different then from those of the present, and Mr. Barnard had hoped that precise measures with the large telescope would reveal internal motions within a few years. He extended his triangulations to many other globular clusters until he had finally included in his program twenty clusters. In spite of his ardor and his experience as a photographer, Mr. Barnard still found it difficult to recognize the superior advantages of the measurement of star clusters on photographs with the use of rectangular co-ordinates. He put his trust in the filar micrometer more than in the measuring machine, particularly because he could recognize certain of the cluster stars as triple which were confused in a single image on the photograph then at hand, taken with an instrument of one-fifth the focal length of the great refractor. A very few years later, when remarkably fine photographs had been secured by Ritchey with the 40-inch telescope, through a yellow filter and with the double-slide plate-holder, Mr. Barnard measured some photographs of the clusters, and in subsequent years took some equally good ones himself. The excellent accordance between his measures on the negatives and those he made visually with the micrometer was to him an evidence that astrometric investigations could be satisfactorily made by photography; to us this accordance was a demonstration of Barnard's extraordinary skill at the telescope with the micrometer. Similarly, when his visual determination of the parallax of Krueger 60 was very closely confirmed by Schlesinger's measures on plates he had taken with the 40-inch telescope, it convinced Barnard that good parallaxes could be obtained by the new photographic method; while for us it was again a demonstration of Barnard's great skill as an observer.

It was probably no small disappointment to Mr. Barnard that his measures in the clusters, continued for nearly twenty-five years, yielded so little in the way of proper motions—in fact, it could hardly be asserted that a single one of the cluster stars showed an appreciable motion with respect to its fellows. From what we know now, it would have been better to omit much of this labor by visual methods and to trust to photographic records made from time to

time for the establishment of the motions which certainly must exist, but which will evidently require a long lapse of time for accurate determination. It will be no small task to evaluate these micrometric measures which were expressed in position angles and distances and referred to selected stars in the clusters; thus, in Messier 5, 239 stars were included; in Messier 13, 247; and in several other clusters the number runs over 100. The measures will certainly represent accurately the positions of the selected stars during the score of years that they were under Barnard's observation. Plans were begun some fifteen years ago for the publication of these measures; but they were delayed in the natural hope that with a longer time some evidences of motion would be established. Considerable attention was given during this work to following changes in brightness of some of the variables, and a few new variables were discovered by Professor Barnard in the clusters. He observed, in particular, Bailey's No. 33 in Messier 5, and determined its period with great precision, contributing half-a-dozen papers to the discussion of this star alone during the score of years that he observed it. At first he thought that the period was constant, but later the continued observations showed that it first lengthened, then shortened.

Although Mr. Barnard would naturally not be regarded as a regular observer of variable stars, he nevertheless discovered some ten of these objects, most of them visually, and he followed particular ones for many years; thus, he published three papers on the period and variation of RS Aquarii, which he discovered visually in 1898. He also followed rather closely several especially interesting stars of this sort, discovered by others, which required large optical power when they were near minimum.

The novae were of especial interest to him: he determined their positions micrometrically with great precision with respect to neighboring stars; he estimated carefully their fluctuations in light and noted the change in focus which resulted from their change in spectrum when the stars were too faint to be observed spectroscopically; he examined them minutely with the great telescope, to detect the presence about them of nebulous shells or phenomena of that nature. He, in fact, discovered visually, in the summer of

1892, the nebulous ring about Nova Aurigae. He included in his studies most of the historical novae for which the positions could be determined—all of this, with the 40-inch telescope. He was an independent discoverer of Nova Aquilae on the night of June 8, 1918, the date of the American eclipse. After his return to the Observatory he found that he had photographed the star on fifty-four dates during the preceding twenty-five years, the Willard lens having been used on four dates and the Bruce telescope on the remainder. He then determined the star's brightness on these plates. His observations of this character were very numerous; thus, he contributed no less than fourteen papers or notes to cover Nova Persei of 1901, and eight such papers on Nova Aquilae of 1918.

In view of the great range of temperature through which micrometric measurements are made with the 40-inch refractor, extending from $-25°$ F. ($-32°$ C.) to $+100°$ F. ($+38°$ C.), he began, in 1897, a series of control measures of the difference in declination between Atlas and Pleione. These observations were made on 506 nights during the past twenty-five years, and thus constitute a great mass of valuable unpublished material bearing both on the constancy of the telescope and micrometer and that of the stars themselves.

At the Yerkes Observatory he kept up his micrometric observations of the fainter satellites of the planets, which he had begun at the Lick Observatory, and contributed to the *Astronomical Journal* ten papers of observations of Saturn and several of Phoebe, the ninth satellite, which he caught as a very faint object in the opposition of 1904, when the planet was 17° south of the equator. At the oppositions of 1906 and 1912–13, when he had a good ephemeris of the satellite, he observed it several times, and estimated it to be of the fourteenth magnitude. We believe that Professor Barnard's measures with the 40-inch telescope are the only visual determinations of the position that have yet been made of this difficult satellite. He observed visually Perrine's sixth satellite of Jupiter, and published his measures in three papers.

Professor Barnard took part in the campaign for observation of the asteroid Eros, during the opposition of 1900 and 1901, for the determination of the solar parallax. His extensive measure-

PLATE II

Star Cloud in Sagittarius (R.A., $18^h 7^m$; Dec.,—18° 15′), Photographed with the 10-inch Lens of the Bruce Telescope by E. E. Barnard. Exposure, $4^h 30^m$.

ments appeared in Volume II of the *Publications of the Yerkes Observatory*, pp. 79–116, issued in 1903.

In 1897 Miss Catherine W. Bruce, of New York, at the solicitation of Professor Barnard, had given to the University the sum of $7,000 for providing a photographic telescope of the highest type of excellence with which he could continue his photographic investigation of the Milky Way and comets. Experiments were at once begun with various types of portrait lens, some of them furnished by Mr. Brashear, in order to find which was the most suitable objective for the purpose. At this time the cameras were strapped to a small equatorial, which was later installed for instruction at the University. This task of finding a suitable objective was continued for several years, and in December, 1899, the quest led Mr. Barnard to Europe, for he was determined to secure an objective which would represent the highest quality attainable in optical construction. Several of the leading European firms made small objectives for the test, but choice was made of the 10-inch doublet produced by John A. Brashear, of Allegheny.

The small wooden observatory for the Bruce telescope, having a dome 15 feet in diameter, was erected, in 1904, at a point 350 feet from the great dome and a less distance from Mr. Barnard's own home. The interest accumulated on the Bruce fund was sufficient to pay for the building. Warner & Swasey had provided for the telescope the excellent mounting of a new pattern particularly well adapted for the purpose. Besides the 10-inch doublet, the mounting carried a Voigtländer portrait lens of $6\frac{1}{4}$ inches aperture, which had been refigured by Brashear, and a 5-inch guiding telescope. A description of the Bruce telescope and its building, with reproductions of two photographs of the Milky Way taken with it, was published by Professor Barnard in the *Astrophysical Journal*, **21**, 35, 1905.

Professor Barnard was now provided with equipment for his work, which he had awaited for some years. When the sky was clear and not rendered useless by the obnoxious presence of the moon, Professor Barnard was generally to be found there making a long exposure on some part of the Milky Way, or on a comet, unless he had an assignment with the 40-inch telescope. Plate II

illustrates the remarkable character of Professor Barnard's photographs of the Milky Way. It is reproduced from the article, "Dark Regions in the Sky Suggesting an Obscuration of Light," which appeared in this *Journal* in 1913, **38,** 496–501 (Plate XIX), and depicts the smaller star cloud in Sagittarius. It includes a small black spot which was formerly called a dark hole, but which we now believe to be an intervening mass of obscuring matter.

He was unhampered by any administrative or editorial duties, and free from any engagements in the classroom, so that he was able to gratify to the full his passion for observing. To him, a night at the great telescope was almost a rite—a sacred opportunity for a search for truth in celestial places. Rarely has a priest gone up into the temple with a deeper feeling of responsibility and of service than did this untiring astronomer go up into the great dome. He was usually ready before the sun had set, and impatiently waiting until the darkness should be sufficient for him to "get the parallel" for the thread of the micrometer before he could observe fainter objects. During the day preceding one of his nights, his associates in the Observatory were generally conscious of his keen anxiety for a clear sky, as evidenced by a frequently repeated nervous cough, which was always worse if the prospects for the night were unfavorable.

It was a marvel to all of us that his bodily strength was equal to the tasks which he put upon himself. He was accustomed to get on with very little sleep, and if the night was cloudy he could never trust himself to relax, but was constantly on the lookout for a possible clearing of the sky. Nevertheless, he often appeared in his office by seven o'clock in the morning, and began work on the reduction of his observations of the night before. He was a very painstaking and accurate computer, and it was rare, indeed, that the positions of any celestial objects measured by him required correction for any numerical errors after they were published. From about 1906 he had the valuable assistance of Mrs. Barnard's niece, Miss Mary R. Calvert, who helped in his computations and in his correspondence, and in filing and cataloguing the great number of photographs and reduction sheets which he accumulated.

The nebulous regions of the Milky Way were always of much interest to Mr. Barnard, and he early discovered on his photographs

great nebulous areas which had not been previously suspected. He investigated many cases of nebulous stars, or of stars which seemed to be involved in "nebulosity," a word which he commonly used to describe vague and indefinite nebulous matter, generally of great extent. In some cases the term may represent a real distinction between a gaseous nebula and that which yields a continuous spectrum, sometimes probably due to light from a stellar source reflected by finely divided matter. The following quotation is from one of his early papers, entitled "The Great Nebula of Rho Ophiuchi and the Smallness of the Stars Forming the Groundwork of the Milky Way":[1]

> For many years this part of the sky troubled me every time I swept over it in my comet seeking; though there seemed to be scarcely any stars here, there yet appeared a dullness of the field as if the sky were covered with a thin veiling of dust, that took away the rich blackness peculiar to many vacant regions of the heavens. This was fully fifteen years ago, at Nashville, Tennessee, when I searched for comets with a five-inch refractor.
>
> After going to the Lick Observatory, I still noticed this peculiarity of that part of the sky, and finally found that two small stars north of Antares were involved in nebulosity and that the whole region seemed to be covered with a very weak diluted nebulosity. . . . .
>
> This part of the sky coming within the sphere of my work in photographing the Milky Way, on March 23, 1895, I made a photograph of it with $2^h\ 20^m$ exposure. The resulting negative showed a vast and magnificent nebula, intricate in form and apparently connected with many of the bright stars of that region including Antares and Sigma Scorpii.

Professor Barnard's studies of such objects may be indicated by the titles of some of his later papers on the subject, which are as follows:

"A Great Photographic Nebula near Pi and Delta Scorpii," *Astrophysical Journal*, **23**, 144–147, 1906.

"The Great Photographic Nebula of Orion, Encircling the Belt and Theta Nebula," *Astronomy and Astrophysics*, **13**, 811–814, 1894.

"Diffused Nebulosities in the Heavens," *Astrophysical Journal*, **17**, 77–80, 1903.

"On a Nebulous Groundwork in the Constellation Taurus," *Astrophysical Journal*, **25**, 218–225, 1907.

"On a Great Nebulous Region and on the Question of Absorbing Matter in Space," *Astrophysical Journal*, **31**, 8–14, 1910.

[1] *Popular Astronomy*, **5**, 227, 1897.

"The Exterior Nebulosities of the Pleiades, with a Drawing from the Different Photographs; and on the Appearance of the Involved Nebulosities of the Cluster with the 40-Inch Refractor," *Monthly Notices of the Royal Astronomical Society*, **60**, 258–261, 1900.

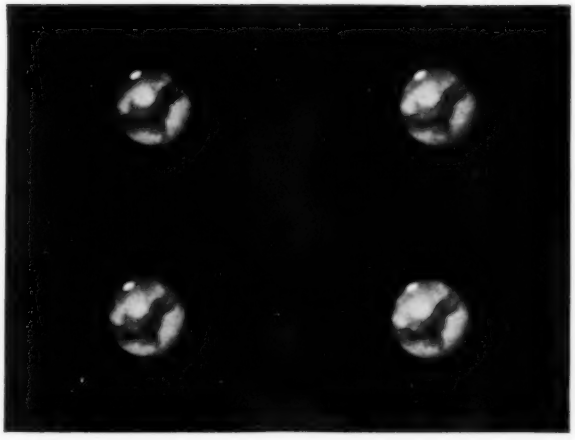
Plate III of this article gives an example of one of his photographs of these nebulous regions, and is taken from his paper entitled, "Some of the Results of Astronomical Photography Pertaining Specially to the Work with a Portrait Lens," which appeared in *Proceedings of the American Philosophical Society*, **46**, 417–429, 1907.

Professor Barnard had early formed a plan for securing a photographic chart of the Milky Way, and he was quick to accept an invitation from Professor Hale to bring the Bruce telescope to Mount Wilson for photographing particularly the southern portions of the Galaxy, in so far as they could be reached from that latitude. The telescope was, accordingly, transported to Mount Wilson, under the auspices of the Carnegie Institution of Washington, in January, 1905, and Professor Barnard spent about nine months on the mountain, engaged in this work. The telescope was back in its own dome at Williams Bay before the end of the year, and for the next seventeen years was always available for Mr. Barnard's use, being very seldom employed by any other observer.

In 1907, the Carnegie Institution undertook to publish the *Atlas of the Milky Way*, when it should be ready, and during several years search was made for the best mode of reproduction of the pictures. Careful experiments were undertaken by experts in photogravure, and with the heliotype process, but the degree of perfection desired could not be quite attained. Finally, Mr. Barnard accepted the suggestion that photographic prints would most faithfully reproduce the wonderful details of the original negatives. Accordingly, with infinite pains, he made positives from the original negatives and then second negatives from which the prints could be prepared. In this way, the contrast in faint regions was increased and details were brought out which might otherwise have been lost. A firm of commercial photographers in Chicago, A. Copelin and Son, personally well known to Mr. Barnard, undertook the task of making

PLATE III

a



b

a) Mars, as photographed by E. E. Barnard with the 40-inch refractor.

b) Nebulous region of Gamma Cygni, photographed with the Bruce telescope by E. E. Barnard. Exposure, $6^h\ 30^m$.

the necessary number of 700 prints from each of the 50 negatives selected to represent the Galaxy. For two years, beginning in May, 1915, Mr. Barnard made frequent trips to the city and personally inspected each of the 35,000 prints, rejecting hundreds and even thousands of those which seemed to him to be lacking, in some detail, the high quality of excellence which he desired to be maintained.

It was very difficult for Mr. Barnard to take time from the reduction and discussion of current observations in order to devote himself to the descriptions of these photographs which were to be a part of the *Atlas*. He was also constantly finding new points of interest, as he studied each photograph in detail, which led him to desire new photographs centering on special regions, or having longer exposures than he had previously given. The publication of this *Atlas* was accordingly delayed, but, fortunately, Mr. Barnard had been prevailed upon to give more time to the completion of the text, and it had been finished, so far as the 50 regions illustrated were concerned. It is to be regretted that he had not written the introduction, which would have summed up his views on the structure of the Milky Way, based upon a personal knowledge more intimate than that possessed by any other person. His notes on the introduction are fragmentary, but they can be used, and it is hoped that the *Atlas* can be published before the close of 1923, in essentially the manner in which Mr. Barnard would have desired it, and accompanied by charts from drawings giving the co-ordinates of the region of each photograph, with a designation of the important features.

During the last decade, Mr. Barnard had taken a special interest in the dark markings in the Milky Way. At first he called them vacancies, and it was only gradually that he was led to the view that they were, after all, in many instances, dark objects projected against the Milky Way and absorbing its light. The titles of some of his papers show this gradual transition in the interpretation of these extraordinary structures. We may cite from his articles on this subject, the following:

"Small Black Hole in the Milky Way," *Astronomische Nachrichten*, **108**, 369, 1884.

"On the Vacant Regions of the Sky" (3 plates), *Popular Astronomy*, **14**, 579–583, 1906.

"Dark Regions in the Sky Suggesting an Obscuration of Light" (2 plates), *Astrophysical Journal*, **38**, 496–501, 1913. This is a paper containing a negative reproduction of the extraordinary dark marking near Zeta Orionis which has lately been so successfully shown on a photograph taken by Professor J. C. Duncan,[1] with the 100-inch reflector at Mount Wilson.

"Some of the Dark Markings of the Sky and What They Suggest" (2 plates), *Astrophysical Journal*, **43**, 1–8, 1916. In this paper, he says:

> An important fact that may come from our knowledge of the existence of dark nebulae is that their masses must be much greater than would be assumed for the ordinary nebulae, because they are prefectly opaque and must be relatively dense, and hence comparatively massive. If this is so, then, we must take into account these great masses in a study of the motions of the stars as a whole.

In that paper (Plate I) he placed side by side a luminous gaseous nebula and a dark object of very nearly the same shape: the resemblance is striking.

"On the Dark Markings of the Sky, with a Catalogue of 182 Such Objects," *Astrophysical Journal*, **49**, 1–23, 1919.

The last-named paper summed up his studies of these objects, which will doubtless be designated in the future by the numbers which he assigned to them in the catalogue.

A very important question in recent years has been the proper location in our stellar system of the globular star clusters. From his studies of their appearance on his photographs of the Milky Way, Professor Barnard was led to the opinion that the clusters are in some instances obviously projected against the background of the Milky Way. His paper, "On the Comparative Distances of Certain Globular Clusters and the Star Clouds of the Milky Way,"[2] seems not yet to have received quite the attention that it deserves. We may quote from it the following:

> Just as the great star clouds of the Milky Way act as a background against which non-luminous masses may be seen in dark relief, they must also act as a

[1] See *Astrophysical Journal*, **53**, 392, 1921.

[2] *Astronomical Journal*, **33**, 86, 1920.

screen and thus hide any object that is behind them. This gives us a means of inferring the relative distances, etc., of many of the great globular clusters. The rich regions of Sagittarius and Aquila, in which some of the finest globular clusters occur, are specially remarkable for their density. That these clusters are nearer than the great star clouds is evident, for they would not be seen through the star clouds if beyond them.

He cites as particular examples, N.G.C. Nos. 6266 (M 62), 6273 (M 19), 6293, 6304, 6333 (M 9), 6528, 6656 (M 22), and 6712.

Although Professor Barnard had given great attention to the surface markings of the planets, it was not until 1909 that he began experiments in photographing the planets with the large refractor, employing a secondary magnification. It will be understood that the direct images of the planets are so small, even in an instrument of long focus, that the grain of the plates makes it impossible to secure a satisfactory photographic enlargement. This work required great skill and patience, because, as Professor Barnard said:[1] "Better conditions are required for successful work in this direction than for visual observations. One can do much visually under conditions where the best definition is only momentary, but for these enlarged photographs any break in the definition for even a single second during the exposure means injury or total ruin to the image. In all the exposures, though of only a few seconds' duration, it was necessary to guide the telescope to keep the image stationary. This was done by bisecting the polar cap by cross-wires (spider threads) in the focus of the long guiding finder ($61\frac{1}{2}$ feet focus) of the 40-inch telescope." It was intended that a full description of this photographic work on planets should be published in this *Journal*, but Professor Barnard never found time to do this. On Plate III herewith are shown four of these enlarged images of Mars which were taken on the same photographic plate at short intervals, in the hope of catching moments of the best definition. He obtained also pictures of Jupiter and of Saturn, but instants of the finest seeing when such work was in progress were too rare to yield absolutely satisfactory pictures. When visiting Mount Wilson in 1911, Mr. Barnard obtained fine photographs of Saturn with the 60-inch reflector.

[1] *Monthly Notices of the Royal Astronomical Society*, **71**, 471, 1911.

We have mentioned before that Mr. Barnard's early interest in the photography of comets and their tails did not abate after the Bruce telescope was put into operation at the Yerkes Observatory. He secured fine series of photographs of all that appeared in our sky, of which may be particularly named: Giacobini's of 1905–1906, Daniel's of 1907, Morehouse's of 1908, Halley's of 1909–1910, Brooks's of 1911, Delavan's of 1914. Of these, Comet Morehouse of 1908 and Brooks of 1911 exhibited the most remarkable activity in their caudal demonstrations, and their eccentricities kept Mr. Barnard almost constantly at the telescope while it was possible to photograph them.

The return of Halley's Comet was awaited with the keenest anticipation by Mr. Barnard. He took many photographs of the region where it might be expected in 1909, and followed it persistently after it was revealed on Professor Max Wolf's plate of September 11 of that year. The records of previous appearances of Halley's Comet had been most carefully studied by Mr. Barnard, but there were many points on which the history was silent or incomplete. He determined to provide against this deficiency for the return of 1910. He kept very full notes on all his observations during the twenty months through which he was able to follow the comet, and embodied these in a long paper appearing in the *Astrophysical Journal* for June, 1914, entitled, "Visual Observations of Halley's Comet in 1910" (**39**, 373–404). In this paper he says: "Halley's Comet at its return in 1910, though a brilliant and interesting object to the naked eye—especially in the month of May—was, nevertheless, a disappointment when considered from a photographic standpoint. It is safe to say that it did not give us any new information concerning these strange bodies." The expected passage of the tail of the comet so close to the earth as to envelop it on May 18–19, 1910, kept Mr. Barnard on the *qui vive*, and the sky was watched throughout the day as well as the night with the greatest of care. Mr. Barnard felt amply rewarded for his pains by the spectacle of the tail in the early morning of the 19th, when he could map it visually for a length of 120 degrees; even on the preceding morning he had been able to record its length as 107 degrees. He last saw the comet a year later, on May 23, 1911, when he secured a

position of it, with some difficulty on account of its faintness, with the 40-inch telescope.

In order to have observations of this comet made in longitudes otherwise unoccupied, the Committee on Comets of the American Astronomical Society, of which Professor Barnard was an active member, secured a grant from the Bache fund of the National Academy of Sciences, which made it possible to send Mr. Ferdinand Ellerman, of the Mount Wilson Observatory, as an observer at Diamond Head, Hawaii. Mr. Barnard spent considerable time in preparing his part of the report of the Committee, which was printed in the *Publications* of the Society in 1915.

It will be understood that in addition to his photographic observations of comets, Professor Barnard was always obtaining their positions with the filar micrometer of the 40-inch telescope, whenever such positions were necessary, upon the first appearance of a comet or after it became too faint for moderate instruments. It may seem a little singular that the large number of long exposures made by Mr. Barnard on the Milky Way did not lead to the discovery of other new comets; but such was the case, and we may well believe that this possibility was not overlooked by one to whom comets had meant so much in his earlier career. In addition to those already mentioned, he was the first to observe, at their predicted return, Encke's Comet in 1914 and Pons-Winnecke in 1921. On a plate taken while he was at Mount Wilson in 1905, he found, some months later, the impression of a comet, which received the name, 1905 f, but was not observed elsewhere.

In spite of Professor Barnard's passion for exact measurement, he still regarded his splendid photographs rather from the point of view of a photographer than from that of an expert in measurement; of course, whenever it was necessary he obtained the positions of comets or other objects on the negatives, but in a general way he had these two distinct attitudes of mind in his work. He was somewhat reluctant to feel that the photographic procedure in astronomy could in many cases supersede the older visual methods for which, in some respects, a much higher degree of expert skill was necessary. His collection of some 1400 negatives of comets contains material on which a vast amount of measurement could be made.

and we trust that this will sometime be done in the study of the peculiar internal motions of comets and their tails. The negatives of the Milky Way and of fields of the sky taken by Professor Barnard at the Yerkes Observatory number nearly 4000, and these constitute a rich field for investigation of stellar motions, for discovery of variable stars, and for statistical studies of the structure of the universe. It is hoped that these plates, which extend over nearly a score of years, may soon be investigated under the "blink" comparator for motions and variables, and it is certain that the full study of this splendid series of photographs will bring to light many important facts.

Occasionally, Mr. Barnard had time to investigate pairs of plates under the "blink" comparator; thus, on comparing a plate taken in May, 1916, with one of the same field he had taken with the Willard lens in August, 1894, he discovered the star in Ophiuchus having a proper motion of $10''.3$ per year, the greatest proper motion thus far detected. This motion was, in fact, so unexpectedly large as to make the discovery very difficult, but the plates were numerous enough to confirm its reality. The position of the object, familiarly known by our staff as Gilpin, was carefully measured by Mr. Barnard with the filar micrometer. Its parallax was investigated here and at other observatories, and was found to be $0''.53$, corresponding to a distance of 6.1 light years, thus making this dwarf the nearest star, after the system of Alpha Centauri. With the large scale of the 40-inch telescope, photographs taken a week apart make the proper motion evident and measurable!

Professor Barnard was deeply interested in eclipses of the sun, and he secured with a visual lens some excellent photographs of the corona at the total eclipse of January 1, 1889, at The Willows, a point in California not far from Mount Hamilton.

In 1900, at the station of the Yerkes Observatory at Wadesboro, North Carolina, he was again favored with a clear sky and secured excellent photographs with the horizontal telescope of $61\frac{1}{2}$ feet focus, but here he denied himself the privilege of a direct view of the corona, remaining inside the spacious camera with Mr. Ritchey to assure the accuracy of the exposures and the perfection of the result. They saw the corona only as it was projected on the photographic film.

Mr. Barnard was invited to join the large expedition to Sumatra organized by the United States Naval Observatory for the total eclipse of May 18, 1901. His station was at Padang Padang, and he planned every detail with the greatest of care for photographs of the corona on a very large scale. The duration of totality was very long, nearly a maximum of six minutes. It was tragic that a thick blanket of clouds totally prevented him from making any observations at that time. He was absent from the Observatory for about six months, and this further deprived him of the opportunity of observing Nova Persei when it was bright.

He was greatly interested in the eclipse of June 8, 1918, and made a trip of inspection with the writer in September, 1917, to select suitable stations in Wyoming and Colorado. He went on with the advance guard of our party to our principal station at Green River, Wyoming, six weeks before the date of the eclipse. He took infinite pains in the adjustment of the horizontal telescope used with our coelostat and could be content with nothing but perfection in the focusing of all the cameras for which he had any responsibility. Unfortunately, a great cloud drifted across an otherwise perfect sky on that afternoon, covering the sun until two or three minutes after totality was over. Mr. Barnard had been again interested in studying the conditions for the eclipse of September 10, 1923, and up to within a fortnight of his death we had still hoped that he might be a member of our party.

Lunar eclipses were not neglected by Professor Barnard: he had photographed successfully, at the Lick Observatory, the eclipses of 1894 and 1895, and it was his custom to make with the Bruce telescope many photographs of the different phases of each lunar eclipse which occurred in favorable weather. With that instrument he also kept a photographic record of all interesting conjunctions of the planets and similar occurrences.

The displays of the aurora, which occur frequently in Wisconsin, were a delight to Professor Barnard, and he recorded their details fully and minutely. Two extended papers based on his observations from 1897 to 1909 appeared in this *Journal*, and his notes covering almost another solar cycle of the aurora are still unpublished. He also gave attention to the self-luminous night haze, which his long vigils had given him unusual opportunities to observe,

and he presented two papers on the subject to the American Philosophical Society, one in 1911 and the other in 1919.

We thus find him a keen observer of nature in most of its visible phases. The meteors did not escape him or his photographic plate, nor did the seventeen-year locusts at their regular recurrence. In the growth of the trees which he had planted about his home he had great satisfaction, and he had much pleasure in following the development and planting of the grounds of the Observatory, when that became possible a few years ago.

In his Will, Professor Barnard bequeathed to the University of Chicago his home, as a memorial of his wife, whose death occurred on May 25, 1921. To the Observatory, he left also his scientific books and the medals and awards he had received in recognition of his notable services to science.

Professor Barnard's home had been a center of generous hospitality for a quarter of a century, and nowhere was he more entertaining than as host in his own home. He was full of humor and could tell most amusingly of his experiences in early life and of his travels. It has been the writer's good fortune to make many railroad trips with him, and he was always a most agreeable companion. He was shy and restive in larger companies where he was not well acquainted with the other guests, and was often quite nervous before giving a lecture on a subject with which he was perfectly familiar. After he was well started in an address he quite lost this shyness and would describe the intimate details of his pictures in a charming way. He never spoke more interestingly than in one of his last lectures which he gave one evening, on the subject of comets, at the meeting of the American Astronomical Society at the Yerkes Observatory in September, 1922.

Always mindful of the difficulties that he had to overcome in his early beginnings as an astronomer, Professor Barnard was most generous in giving advice and assistance to all sincere aspirants for knowledge of astronomy who approached him with questions, by letter or in person, and he gave his time freely to such, in exhibiting and explaining his most significant photographs. He willingly took his turn in speaking to the large numbers of visitors admitted to the Yerkes Observatory on Saturday afternoons, and often stayed long

after the closing hour in explaining details to those who had evinced a real interest. He was most kind to other workers in astronomy, and tolerant in expressing opinions of them, even though their views might differ very greatly from his, and though he might regard them as radically wrong. He avoided controversy, and seldom took his pen to oppose the views of others.

Professor Barnard was not a teacher. He had missed the inspiration and opportunity of studying astronomy under some gifted enthusiast. He had, of course, profited by taking part in the work at an institution so well planned and organized as was the Lick Observatory by Director Holden, and had received much benefit from the sane counsel of his seniors there, particularly from Mr. Burnham; but he did not realize from experience the mutual importance of the relation of teacher and pupil, or know the satisfaction of the teacher in having an apt follower in his research to whom he may pass on the acquisitions of his years of study. Mr. Barnard could not bring himself to lose time at the telescope in having a pupil take part in measurements, which he could himself make so much better, and he begrudged the possible loss, in quality, of a photograph if someone less skilled than himself took some part in the guiding. Accordingly, he trained no one to be his successor; he left no disciple who could take up his work after receiving the benefit of his unequalled experience as an observer and of his exceptional knowledge of the heavenly bodies.

Mr. Barnard was striken with diabetes early in the year 1914, and had to undergo the severe privation, by the doctor's orders, of giving up observations with the large telescope for a year. As a result of his obedience, his health was greatly improved, and for the past seven years he kept up his observing most industriously and really beyond the measure of his bodily strength. It was regarded by the director of the Observatory as no small part of his duties to see that such a man should be induced to spare himself as much as possible and to restrict his night work both to save him from exhaustion and to gain time for the reduction and discussion of his great accumulation of observations. But it was almost impossible for Mr. Barnard to keep away from the Bruce photographic telescope when the sky was clear and the moon did not interfere.

He was greatly affected by the death of his wife in May, 1921, after a brief illness and after forty years of married life in which she had devoted herself completely to his comfort. They had no children, and thus Mr. Barnard missed the joys and responsibilities of parenthood, even as he had himself missed the experience of the relation of son to father.

His final illness was of only six weeks' duration, and began rather acutely. The best of medical skill was given him, and up to a short time before his death the specialist was hopeful of his recovery. He died at eight o'clock on the evening of February 6, and simple funeral services were held on the following day in the rotunda of the Observatory, which seemed to us the appropriate place. The interment was at Nashville, after services attended by many friends in his native city and from his Alma Mater. He had always been highly appreciated at Nashville, and one of the interesting evidences of this was the erection, not long ago, by the Nashville Automobile Club, in co-operation with the Nashville Historical Committee, of a tablet at the place in the city where the young enthusiast discovered his first comet in 1881.

Measured by the calendar, his life was but little more than sixty-five years, but, by the number of hours he had spent under the nocturnal sky or in the domes, his period of activity was more than that of many who had passed four score years.

His services to science were recognized by the learned societies. He was vice-president of the American Association for the Advancement of Science in 1898, and delivered an address upon "The Development of Photography in Astronomy." In the same year he was elected a foreign associate of the Royal Astronomical Society. He became a member of the American Academy of Arts and Sciences in 1892, of the American Philosophical Society in 1903, and of the National Academy of Sciences in 1911. He was made a director of the B. A. Gould Fund, under the auspices of the National Academy, in 1914, and at the same time an associate editor of the *Astronomical Journal*. He had been for three years (1892–1894) associate editor of the journal *Astronomy and Astrophysics*. In addition to the medals mentioned heretofore in this article, he received from the French Academy of Sciences in 1893 the Arago

gold medal, and in 1900 the Janssen gold medal; he was the recipient of the Janssen prize of the Astronomical Society of France in 1906, and was awarded the Bruce gold medal of the Astronomical Society of the Pacific in 1917. The last-named society had three times awarded him the Donohoe comet medal. He was given the honorary degree of Doctor of Science by Vanderbilt University in 1893, and that of Doctor of Laws by Queen's University, of Kingston, Ontario, in 1909.

The voluminous character of his contributions to astronomical literature has already been indicated, but we may add that a card catalogue of his writings includes no less than 900 items, without being complete. A bibliography of his articles which appeared since his connection began with the University of Chicago in 1895 has been published in the list of publications of the faculties issued annually by the University of Chicago and also collected in two special volumes of this character covering the first twenty-five years of the work of the University. These contain the titles of 377 articles and 6 book reviews by Professor Barnard, to which number will be added, as time permits their preparation, numerous papers covering his unpublished observations.

His last measurements with the 40-inch telescope were made on the night of December 16, 1922, when he secured the position of Baade's Comet; his last visual observations with that instrument were on December 21, when he made nineteen estimates of the brightness of Nova Persei, referred to thirteen comparison stars; and his last use of that instrument was later on that night when he made a photograph of the cluster, Messier 36, with an exposure of two hours. A photograph of the region of Gamma Leonis, made on the following night with the Bruce telescope, closed his long and untiring work with that instrument. His last visual observation was of the occultation of Venus on the morning of January 13, 1923, which he observed from the window of his sick room. Thus closes the record of the astronomical activity of one of the greatest observers of our time, of whom may be truly said

"Aperuit caelos."

YERKES OBSERVATORY
June 1923

INVESTIGATIONS OF PLATE ERRORS WITH THE THERMO-ELECTRIC PHOTOMETER

By HARLAN TRUE STETSON and EDWIN F. CARPENTER

ABSTRACT

Thermo-electric photometer for stellar images.—The improvements in apparatus described in previous articles in this *Journal* have resulted in reducing the time necessary for the measurement of star magnitudes by at least 50 per cent and, at the same time, increasing the sensitivity from 100 to 200 per cent. The probable error of measurement of a photographic star image is ±0.007 mag., so far as the errors of apparatus and manipulation are concerned.

Tests of uniformity of emulsion on photographic plates.—Tests were made to determine the degree of uniformity in the emulsion of the photographic plates, (*a*) by securing equal exposures of an artificial star scattered widely over the plate, and measuring the resulting images with the thermo-electric photometer; (*b*) by exposing restricted but widely scattered regions of the plate to a uniform source, and measuring the opacities as for extra-focal images. The *sensitivity* of a plate was found to be more nearly uniform over the entire surface when the plates were presoaked for one hour after exposure and before development, and allowed to dry on edge in still air. The *probable error due to non-uniformity for extra-focal work* was found to be 0.03 mag. and for *focal work* 0.02 mag. for a single "image" from the photometric measures. A tendency to systematic changes in sensitivity over the surface is indicated.

In articles previously published in this *Journal*,[1] an apparatus and method were described for measuring the magnitudes of stars from photographic plates by means of a thermopile. Although the thermopile could be used simply for the measurement of plate opacities in extra-focal images, it was pointed out that the principal merits and advantages of the thermo-electric photometer lay in the measurement of focal images, where it appeared a higher degree of precision could be obtained by this method than by other methods applicable to focal images.

As has been pointed out,[2] the most serious drawback to a considerable gain in precision in photographic photometry seems to lie in the errors inherent in the plate itself. Previous investigations have left considerable uncertainty as to the actual order of accuracy which the plate may be relied upon to render in photometric work. In any investigation of plate errors, it appears at once that the method of measurement must exceed in accuracy the reliability

[1] *Astrophysical Journal*, **43**, 253 and 325, 1916.

[2] *Ibid.*, **43**, 278, 279.

of the plate, for it is only by such means that we can make reliable deductions which may lead to improvements in the photographic process, or that may render feasible a higher degree of precision in photographic photometry. The thermo-electric photometer, therefore, is peculiarly adapted to such an end.

Before describing the methods and results of the plate tests, mention should be made of some important improvements in the design and construction of the photometer since the publication of the description of the apparatus in the previous account.[1]

IMPROVEMENTS IN THE APPARATUS

The general scheme of the arrangement has remained unchanged, and is that depicted in drawing in the earlier article to which reference is again made. However, by refinements in the optical system and the use of a newer type of galvanometer, a remarkable gain in sensitivity has resulted, which has made possible the elimination of the 200 watt 50-volt lamp as a source, and the substitution in its place of a 20 watt 6-volt lamp of standard make. This lamp contains a filament of tungsten wire in the form of a closely wound helix of small dimensions. Its efficiency in the operation of the photometer depends as before upon the proper orientation of the filaments in such a way that the images formed by the condensing lens shall cover the diaphragm with approximately uniform illumination.

This tenfold reduction in the wattage of the lamp has not only made possible the use of a small portable storage battery in place of the 50-volt battery, but avoids undue heating of the emulsion of the plate during the process of measurement, thereby producing more equable conditions of temperature. In spite of the marked reduction in the energy of the source, it has become possible by virtue of the improved galvanometer to employ diaphragms 40 per cent smaller than had previously appeared practicable, so that for faint star images of the order of 0.1 mm in diameter a diaphragm 0.3 mm in diameter is employed, giving values of δ (the fall in galvanometer deflection for a given star image) 80 per cent greater for a given star image than had been obtained previously with a

[1] *Loc. cit.*

diaphragm 0.5 mm in diameter. The galvanometer now used is a D'Arsonval, type R, manufactured by the Leeds Northrup Company. It has a sensitivity of 2.3 mm per microvolt, an internal resistance of 10 ohms, and a period of 5 sec. when in series with critical damping resistance of 50 ohms. With the outfit as thus described and illustrated in Figure 1, an actual gain in sensitivity of 100 to 200 per cent has been secured.

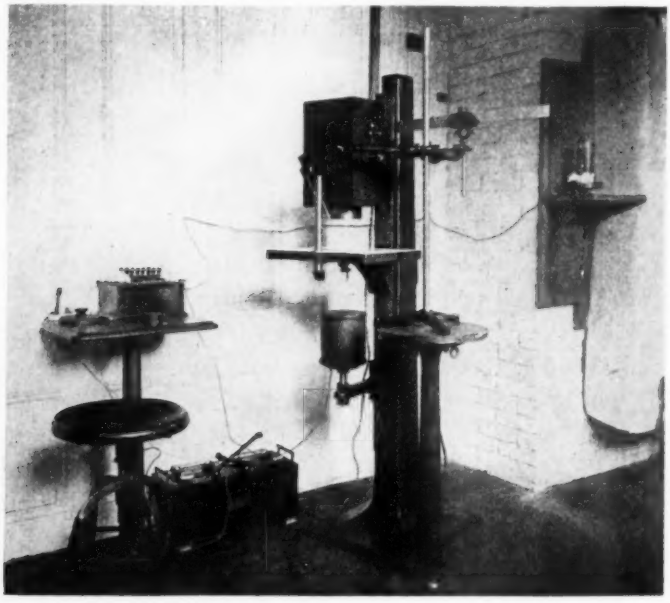


FIG. 1.—The thermo-electric photometer and auxiliary apparatus

More recently, furthermore, the addition of a metallic plate inside the thermopile house just above the thermo elements has facilitated radiation from the cold junctions and reduced from 50 to 75 per cent the time consumed in establishing thermal equilibrium. Recent work shows that the time necessary for the measurement and reduction of a star magnitude, making five settings for each image, is about two and one-half minutes, with a probable error of measurement of 0.007 mag.

By employing three right-angled prisms and an adjustable mirror, it was found possible to combine the microscope for viewing

the plate with the short-range telescope by means of which the centering of the star image upon the thermopile is effective. A small lever just below the eye lens tilts a mirror within the tube into either of two positions, allowing the observer to look directly through to the plate surface at the top of the stage, or by way of the three prisms to view the bottom of the well in the thermopile house for the purpose of centering the star image upon the receiving surface of the thermopile.

In manipulation of thermo-electric apparatus, too great emphasis can hardly be stressed upon securing firm contacts not only in the thermopile-galvanometer circuit but in the battery-lamp circuit as well. Any slight irregularity in current flow interrupts the wattage output of the lamp with an instant effect upon the galvanometer deflections.

DESCRIPTION OF THE PLATE-TESTING DEVICE

In devising an arrangement for testing variations in sensitivity over a photographic plate, two fundamentally different methods may be used: (1) to expose a large number of isolated spots on the plate simultaneously to a uniform field of illumination; and (2) to cover the plate with a series of successive exposures equally timed and of the same illumination. The first method of single exposure guarantees equal exposure times for all parts, but presents no little difficulty in devising a source of light which may be trusted to give the same intensity of illumination on all parts of the plate. In the method of successive exposures, we may arrange for each exposure to take place in the optical axis of the system, and by so doing imprint artificial star images over the entire surface of the film by suitably moving the plate after each exposure. The special precautions necessary in this arrangement are to maintain constant the source of illumination, distance of the plate from the source, and time of exposure.

In the present investigation, it was decided to adopt, first, the second of these methods of procedure, since it made possible the photography of artificial star images free from field corrections, which would very closely simulate astronomical conditions.

The apparatus as adopted in its final form for making the plate tests consists of a small artificial star (pinhole diaphragm) illuminated by a 24-watt lamp, fed by an 8-volt storage battery of 120-ampere-hour capacity. The exposures are produced by releasing a pendulum shutter which uncovers the "star" for about one second. The equality of the exposure times is maintained by the isochronism of the pendulum, and can undoubtedly be relied upon to an accuracy well within 1 per cent.

At a distance of 100 cm from the "star" is an anastigmat lens of 16-cm focus, which serves to form the image on the plate to be tested. The ways that carry the plate are mounted on a rotating disk, the axis of which in turn is mounted so as to allow motion in horizontal ways at right angles to the optical axis of the system. This combination of polar and rectangular co-ordinates was adopted to facilitate both construction and manipulation, and minimizes the errors attributable to variation in focus as the plate is moved to bring different parts into the optical axis for the exposures. A series of depressions on the back side of the metal disk carrying the plate and a series of notches on the horizontal ways serve as convenient stops for spring palls which locate the position of each exposure on the plate as it is rotated in position angle and moved horizontally in the ways. The complete apparatus is set up in the photographic dark room of the laboratory, and is operated in total darkness without inconvenience.

A plate properly exposed and developed shows a series of images uniformly distributed over the surface to within about 10 mm of the edge. These images, having received equal exposures, should then all be of equal size and blackness, and, when measured on the thermo-electric photometer, should yield the same magnitude within the experimental errors, *provided* the sensitivity of the film is uniform over the entire surface. This will not be the case, and the discrepancies which result will therefore be a measure of irregularities in the film sensitivity.

In order to interpret the measured irregularities, there must be impressed upon the film a series of images of known magnitude difference. This is accomplished by making additional exposures

while in the testing machine, and varying the aperture of the camera lens by the use of diaphragms giving approximately half-magnitude intervals. The exact values for the diaphragms were computed through measurement of their diameters.

With such a scale of magnitudes, the plate gamma is readily determined from the thermo-electric measures and therefrom the magnitude residuals for each image become known. A number of "Seed 30" plates (4 in.$\times$5 in.) tested in this way showed probable errors of .05–.08 of a magnitude for commercial plates receiving the ordinary treatment in development. As this error was considerably larger than was anticipated, some plate-glass plates were secured through the courtesy of the Eastman Kodak Company, which, it was hoped, would reduce these errors somewhat. It seemed likely that the concavity of the ordinary plate, which from a series of tests was found to vary from about 0.002 in. to 0.008 in. on the 4$\times$5 size, might be responsible for different thicknesses in the emulsion at different parts of the plate. Furthermore, this concavity introduces a small magnitude error for focal images in that the entire film surface cannot be relied upon to preserve a constant relation to the focal plane of the objective.

Comparison of results obtained with the ordinary and the plate-glass plates, however, did not show startling differences, except where the surface of a commercial plate proved unusually poor. The consistently smaller probable error which results from the use of plate glass shows, however, that for work in photometry of the highest precision, plate glass should be adopted as a necessary requisite for the support of the photographic emulsion.

For the purposes of studying the distribution of plate errors, a chart was made of each plate studied, an example of which is shown in Figure 2. A tendency to systematic distribution of plus and minus errors led to the detection of the source in a small change in focus of about 0.0005 in. (0.0012 cm) as the plate carrier was rotated and shifted in the testing machine. Careful measurements with a surface gauge were taken for the focal setting of each point with a plate in the testing machine; and the small variations in focus, thus determined, were plotted against the mean of the magnitude errors of each "star image" for a series of plates. The results

gave nearly a straight-line relation showing a change of 0.1 mag. for a change in focus of 0.0002 cm. When the allowance was made for these systematic errors, the probable error for a single image was reduced about .02 of a magnitude.

Inasmuch as it seems probable that the errors are chiefly introduced during the drying process, due to unequal draining and evaporation of the wash water, numerous tests were made of plates dried

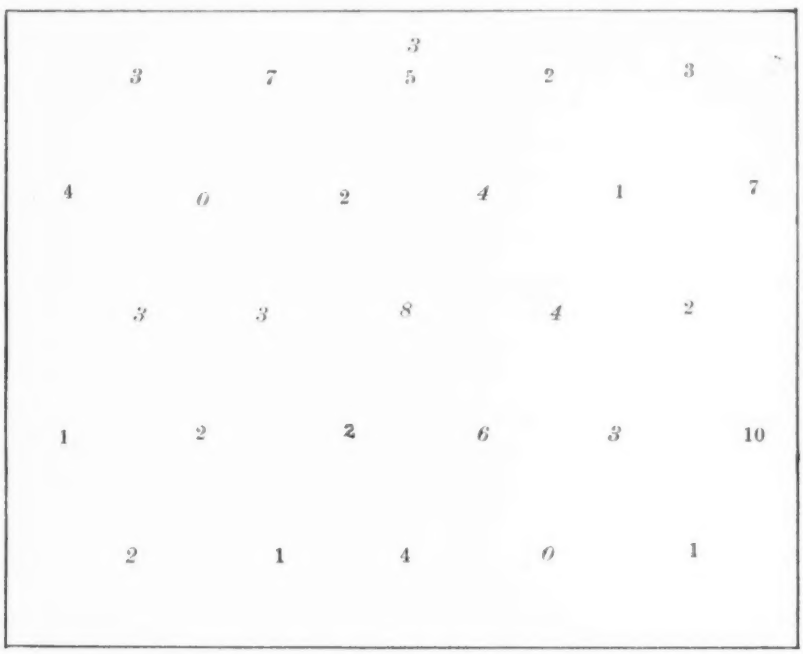


FIG. 2.—Plot showing magnitude residuals for Plate HS 63 P. Roman type indicates positive and *italics* negative residuals. Unit = 0.01 mag.

in different positions, viz., face up, face down, on edge with side down, and on edge with corner down. The result of these tests showed that nothing was to be gained by any different orientation than that usually and most conveniently adopted, i.e., corner down.

To test the effect of speed of drying, plates were dried by force in two ways: (*a*) by use of alcohol, (*b*) by electric fan; and results in both cases showed a considerable increase in the size of errors. Errors were less for plates dried slowly in still air by means of a

drying cabinet consisting of a wooden frame covered with cheesecloth and containing two supporting shelves of coarse wire screening.

Correspondence with Dr. Ross, of the Eastman Kodak Company, led to the experiment of soaking the plates for one hour, preferably in distilled water, just before development. The average probable errors on plates so treated were about one-half that of unsoaked plates. This appears to be an important step. It seems probable that the prolonged soaking relieves certain strains in the gelatin emulsion, resulting in better uniformity both in development and in the subsequent drying.

Test exposures have been made on some plates backed with plate glass and ordinary glass, and including "Seed 27," "Seed 30," "Seed 23," and "Cramer Hi-Speed" emulsions. There seems to be little difference between the fast and slow plates, judging from the plates tested. Experiments were tried with different developers including ferrous oxalate, hydroquinone; and slightly smaller errors have seemed to favor the hydroquinone developer which, as used in the present instance, was compounded as follows:

A		B	
Water (distilled)	100 cc	Water (distilled)	100 cc
Sodium Sulphite	3 gm	Sodium Sulphite	3 gm
Hydroquinone	3.7 gm	Potassium Carbonate	12 gm
Sulphuric Acid	0.4 gm	Potassium Bromide	2 gm

A brief table (I) giving a detailed summary of some of the more recent tests is appended.

The first column gives the serial number of the test plate, the second column the kind of plate—the suffix letter C or P indicating commercial or plate glass, as the case might be. The third and fourth columns give the emulsion number and the kind of developer used. The fifth column gives the probable error for a single image as determined from each plate on the assumption that all errors result from the emulsion itself. The last column gives the same probable error when corrected for the systematic errors of the testing device, due to the slight change in focus as the plate is rotating.

After it appeared that little further variation in the probable error was to be expected from further tests of this kind it was decided to try the first of the two methods mentioned, namely, exposing

simultaneously selected parts of a plate to a uniform source. In doing this, all questions of variation in focus would be eliminated. The plate was accordingly placed in a holder directly behind and in contact with a grid which should give alternate exposed and unexposed regions. The plate was then exposed to a source of illumination rendered as nearly uniform as possible through the use of multiple diffusing screens and was rotated by a motor throughout the exposure so that any lack of uniformity in the illumination should appear as systematic differences in opacity concentric about the geometric center of the plate. Some forty or fifty spots were

TABLE I

Plate No.	Kind	Emulsion	Developer	Prob. Error for Single Image	Corrected Prob. Error
25.....	Seed 30 C	4200–12–53	E.Q.	±0^{M}061	.....
27.....	Seed 30 C	4200–12–53	Ferrous Oxalate	±0.052	.....
31.....	Seed 30 C	4035–26–83	Hydroquinone	±0.037	± .024
32.....	Seed 30 P	4239–4–4	Hydroquinone*	±0.047	± .021
33.....	Seed 30 P	4239–4–4	Hydroquinone*	±0.034	± .015
38.....	Wellington X C	5872 B B	Hydroquinone*	±0.032	± .021
43.....	Wellington X C	5872 B B	Hydroquinone*	±0.065†	.....
62.....	Cramer Hi.–P	24413 A2EN	Hydroquinone*	±0.043	± .022
63.....	Cramer Hi.–P	24413 A2EN	Hydroquinone*	±0.034	± .026
65.....	Seed 30 P	5266–80–27	Hydroquinone	±0.050	± .036

* Indicates that the plate was immersed in water at approximately 70° F. for about one hour before development.

† This plate was an ordinary glass with an unusually poor surface as found from surface measures.

selected on the resulting plates for measurement of opacity with the thermo-electric photometer. Readings on the clear glass channels between the exposed strips were taken in every instance to eliminate glass and gelatine absorption as usual. A system of standard squares of known magnitude differences as used at the Harvard College Observatory by Professor King was imposed for giving the plate gamma. Measures of opacities in this way give a direct indication of the magnitude of the errors which would be involved in the method of extra-focal measures due to lack of uniformity in plate sensitivity. The probable error for a single "image" was found to be of the order of 0^{M}035 or about 50 per cent larger than the results for focal images. Furthermore, decided tendencies to systematic distribution of plus and minus residuals

left little doubt that the major part of the difficulty lies in the manufacture and application of the emulsion to the plate itself and that the use of plate glass probably does not modify the results of extra-focal measures.

CONCLUSION

From the results of the present investigation, the errors in magnitude of star images due to irregularities in different parts of the same plate are of the order of three or four hundredths of a magnitude. These errors are unquestionably but not startlingly reduced by the use of plate glass. It seems unlikely that there is any consistent difference in plates of any of the well-known brands represented, or that the plate errors depend in any direct way on the speed of the emulsion. It does not seem probable that different developers will give very different results, but there is room for further investigation here. It does seem probable that prolonged immersion of the plate in water before development improves the uniformity, and that slow drying likewise favors uniformity.

To summarize results, it appears that the probable error in magnitude of photographic plates may be kept down to the order of about $0^{M}.02$, such results having been attained in the present investigations under the following conditions:

1. Plates soaked in water (65° F.) for one hour between exposure and development.
2. Developed in hydroquinone (modified Wallace formula).
3. Dried in still air, on edge, corner down.

The diameters of the images involved in this investigation were of the order of 0.2 mm.

Measure of opacities of more extended areas, as for extra-focal images, indicated probable errors about 50 per cent larger than for focal images.

ASTRONOMICAL LABORATORY
HARVARD UNIVERSITY
CAMBRIDGE, MASS.
January 1923

THE HYDROGEN BALMER SERIES AND THE IMPOSSIBILITY OF FURTHER CORRECTIONS TO THE QUANTIZING OF HYDROGENIC ATOMS

By ARTHUR E. RUARK

ABSTRACT

Wave-lengths of the Balmer lines H3 to H18.—In *Table I* the values of λ from H_7 to H_{18} are more accurate than any values previously given, but they are not precise enough to yield a definitive value of the Rydberg constant R_H. *Formulas* are obtained for calculating R_H from the wave-length of an unresolved Balmer line. *The main components of* H_3 are separated by 0.0584 A.

The relativity correction only is needed to explain existing observations.—(1) The observed structure of the lines does not admit a correction due to *asphericity of nucleus* or electron; Silberstein's theory shows that if the nucleus and electron have radii of about $3 \cdot 10^{-13}$ cm, the alteration of the lines would be unobservable. (2) H. A. Wilson's correction to the *quantizing of the atom*, due to motion of a part of the potential energy with the electron, is not in accord with experiment. (3) H. S. Allen's formula for the correction due to a possible intrinsic *magnetic moment* of the nucleus is extended to the case of elliptic orbits; a magnetic moment of one Weiss magneton in the nuclei of H or He would distort the fine structure of H and He^+ lines by a readily observable amount; therefore it cannot exist.

Much recent experimental work on the hydrogen spectrum has dealt with the fine structure of the first few Balmer lines, so that the relativistic quantizing of the atom might be tested further. It is possible, however, to arrive at a conclusion more easily by accurate measurement of the wave-lengths of higher members of the Balmer series. In recent papers Professor R. W. Wood[1] has described methods by which he photographed twenty-two Balmer lines, using the light from the central part of a long vacuum tube through which moist hydrogen was flowing. In such a tube the secondary spectrum is nearly absent, and the greatest difficulty in extending the Balmer series is the suppression of the continuous spectrum which masks the faint lines of higher order. In the spring of 1922 Dr. Wood obtained an excellent series of plates in the second and third orders of a 7-inch plane grating, having a resolving power practically equal to the theoretical value; it was used under good temperature control in a 20-foot Littrow mount, giving a dispersion of 1.27 A per mm in the second order at 3800 A. The author undertook to

[1] *Proceedings of the Royal Society*, A, **97**, 455, 1920; *Philosophical Magazine*, **42**, 729, 1921; *ibid.*, **44**, 538, 1922.

measure these plates in order (1) to furnish better wave-lengths for the higher members of the series; (2) to determine the Rydberg constant; and (3) to test the necessity of corrections to the theory of hydrogenic atoms, arising in the asymmetry of nucleus or electron, or in the existence of an intrinsic magnetic moment in either of the two, or, finally, in the possibility that part of the potential energy of the atom may be considered to move with the electron, so as to change its apparent mass. These three corrections have been suggested by Dr. L. Silberstein, Professor H. S. Allen, and Professor H. A. Wilson, respectively.

1. MEASUREMENT OF THE BALMER LINES

The grating measurements of Professor Ames[1] were referred to the Rowland system, and cannot be converted to I.A. without introducing error, while the spectrograms of Dyson, of Evershed, and of Mitchell[2] were obtained under eclipse conditions. The only measures suitable for testing the quantizing of hydrogen are as follows:

Paschen, grating, lines 1–4, *Annalen der Physik*, **50**, 901, 1916.

Meissner, interferometer, lines 1 and 2, *ibid.*

Curtis, grating, lines 1–6, *Proceedings of the Royal Society*, A, **90**, 605, 1914; and **96**, 147, 1919.

The probable error of Paschen's work is 0.004 A; that of Curtis' measurements is smaller because he used from nine to fourteen plates for each line. Probable error is not so good a criterion of precision as the average deviation, but it is certain that both sets of data are very accurate.

The author's wave-lengths are referred to tertiary iron standards; only those lines were utilized which do not show appreciable pole effect and which are assigned the same wave-length by Burns, Meggers, and Merrill,[3] and St. John and Babcock.[4] Seldom was it necessary to use a standard more than 8 A from a Balmer line, and the dispersion was linear, within the limits of the desired accuracy, for a distance of 15 A on either side of the line. The

[1] *Kayser's Handbuch*, Vol. 5.

[2] *Astrophysical Journal*, **38**, 407, 1913.

[3] *Bulletin of the Bureau of Standards*, **13**, 245, 1916.

[4] *Astrophysical Journal*, **53**, 260, 1921.

lines appeared of uniform density and the middle was set on, with a single exception: on two plates H_3 was well separated, due to short exposure, and here the minimum was set on. Each line was measured from three to eight times in each direction on each plate, to reduce error of measurement as far as possible. The data of Meggers and Peters[1] were used in reducing to vacuum. Table I gives the results: If equal weights are assigned to the data of Paschen, Curtis, and the author, we get the following wave-lengths for H_3 to H6 unresolved: 4340.4655, 4101.7346; 3970.0740 and 3889.0575 I.A.

TABLE I

Line	λ Air	λ Vacuum	ν Vacuum	Average Deviation from Mean in A.U.	Number of Plates Used
3	4340.464	4341.6806	23032.5556	.003	2
4	4101.731	4102.8845	24373.0965	.006	2
5	3970.073	3971.1918	25181.3574	.0016	3
6	3889.064	3980.1618	25705.8717	.0017	3
7	3835.397	3836.4813	26065.5513	.0023	3
8	3797.910	3798.9847	26322.8225	.0025	4
9	3770.634	3771.7016	26513.2321	.010	3
10	3750.152	3751.2136	26658.0394	.010	3
11	3734.372	3735.4293	26770.6847	.010	2
12	3721.948	3723.0030	26860.0374	.007	2
13	3711.98	3713.03	26932.17	.....	1
14	3703.86	3704.91	26991.20	.....	1
15	3697.15	3698.20	27040.20	.....	1
16	3691.55	3692.60	27081.19	.....	1
17	3686.83	3687.88	27115.86	.....	1
18	3682.82	3683.87	27145.37	.....	1

H_{13} to H_{18} are correct only to about 0.02 A, because the single plate from which they were measured was jarred between exposures. The wave-lengths were adjusted by comparing the value for H_{12} obtained from this plate with the mean gotten from other plates.

The separation of H_3 was measured on one plate and was found to be 0.0584 A. This result will be discussed elsewhere.

2. CALCULATION OF THE RYDBERG CONSTANTS; TEST OF THE THEORETICAL SERIES FORMULA

Let ν be the wave-number; m_0, the rest-mass of an electron; M_H, the mass of the H-nucleus; h, Planck's constant; $-e$, the electronic charge (electrostatic units); n, n', m, m', the azimuthal

[1] *Bulletin of the Bureau of Standards*, **14**, 697, 1918.

and radial quantum numbers of the final and the initial orbits, respectively. The Rydberg number for hydrogen is

$$R_H = \frac{R\infty}{1+\frac{m_0}{M_H}} = \frac{2\pi^2 m_0 e^4}{h^3 c\left(1+\frac{m_0}{M_H}\right)}. \qquad (1)$$

The constant of Sommerfeld's relativity correction is

$$\alpha = \frac{2\pi e^2}{hc}. \qquad (2)$$

The wave-number of any component of a line is

$$\nu = R_H \left\{ \frac{1}{2^2} - \frac{1}{(n+n')^2} + \alpha^2 \left[\frac{1}{2^4}\left(\frac{1}{4}+\frac{n'}{n}\right) - \frac{1}{(m+m')^4}\left(\frac{1}{4}+\frac{m'}{m}\right)\right]\right\}. \qquad (3)$$

Curtis found empirical formulae with two or three constants which represent his measurements of the first six lines quite as well as (3); therefore, it seems useless to calculate such formulae in the present case and to compare the results with those obtained by using (3). To test this formula we shall utilize the theory in all its details to compute a value of R_H from each line, and shall determine the average deviation of the results from their mean. First we must assume a value of α^2. It is certain that α^2 cannot deviate from 5.315×10^{-5} by more than 0.007×10^{-5}, and ΔR_H is less than 0.004 if $\Delta(\alpha^2)$ is equal to 0.007×10^{-5}; such a variation is negligible.

There are influences which shift a Balmer line from the position predicted by Sommerfeld's theory. Darwin[1] has evaluated the corrections to the relativistic quantizing due to motion of the nucleus, the magnetic forces caused by the motion, and the retardation of potentials. An extra term appears in the coefficient of α^2, such that *all* components of a given line are shifted in frequency by an amount less than $1/7400$ of $R_H\alpha^2/16$, which is negligible.

There is a shift of the center of gravity of a doublet due to the narrowing discussed by Oldenberg,[2] if the two components are

[1] *Philosophical Magazine*, **39**, 537, 1920.

[2] *Annalen der Physik*, **67**, 453, 1922.

of unequal intensities. Roughly, the maxima are shifted toward each other by amounts in the ratio $r:1$, if r is the intensity ratio of the components, and the center of gravity will be moved from its proper position by an amount $r-1/r+1$ times the average shift of the components; the average shift of the components is one-half the narrowing of the doublet, which is obtainable if the doublet separation can be observed. For the intensity ratios of the components of H_3 and H_4 we use values estimated by Professor Birge[1] for usual experimental conditions, viz., 1.2 and 1.1. The observed narrowings are 0.009 A and 0.015 A; it follows that the shifts of mean center for these lines are 0.00041 A and 0.00036 A. The effect is smaller for all succeeding lines, and is negligible for all lines except $H\alpha$ and $H\beta$.

The theoretical formula gives only the positions of single components; we must express the position of the mean center of a Balmer line in terms of R_H, α^2, and the quantum numbers of the components appearing in the fine structure. There are three such components, in the absence of external fields; it suffices to suppose that the fine structure will approximate in position (though *not* in intensity) to that arising from the undisturbed hydrogen atom. The components of the $(M-2)$th Balmer line actually appearing are these: $(3,M-3)\rightarrow(2,0)$; $(1,M-1)\rightarrow(2,0)$ and $(2,M-2)\rightarrow(1,1)$. The first two falls give components comparatively close together, forming the long-λ half of the doublet; the third fall gives the short-λ half. If all six of the possible components could appear, the separation of the outer members of either half would be as follows: H_3, 0.006 A; H_4, 0.003 A; H_5, 0.002 A. Even if all components were to appear with equal strength, the shift of H_3 as a whole could not exceed 0.003 A; the effect would be much smaller for all succeeding lines. Birge's intensity computations for usual experimental conditions show that the changes from the normal patterns are much smaller than those mentioned, in fact, the component $(1,M-1)\rightarrow(2,0)$ is weak compared with the other component of the long-λ half of the doublet, and we shall consider all the lines as simple doublets whose halves coincide with the components $(3,M-3)\rightarrow(2,0)$ and $(2,M-2)\rightarrow(1,1)$.

[1] *Physical Review*, **17**, 589, 1921.

Next we find the centers of gravity of the doublets. The extreme faintness and narrowness of the H_3 doublet (separated only when underexposed) prevented direct measurement of the intensities of its components; a visual estimate showed that it would be nearly correct to use the intensity ratio 1.2, calculated by Birge for an external field of 100 volts/cm. It seemed best to use also the estimates of Birge for H_4 and H_5, viz., 1.1 and 1.05. Let λ_c and λ_e be the wave-lengths of the components $(3,M-3)\rightarrow(2,0)$ and $(2,M-2)\rightarrow(1,1)$; and let λ_0 be the observed vacuum wave-length of the doublet as a whole. If the intensities of the components are in the ratio $(1+f)$: 1, then

$$\lambda_0=\lambda_c-\frac{1}{2+f}(\lambda_c-\lambda_e)=\tfrac{1}{2}(\lambda_c+\lambda_e)+\tfrac{1}{2}(\lambda_c-\lambda_e)\left(\frac{f}{2}-\frac{f^2}{2^2}+\ \ldots\ .\right). \quad (5)$$

With sufficient approximation we have

$$\frac{1}{\nu}\equiv\tfrac{1}{2}(\lambda_c+\lambda_e)=\lambda_0-\frac{f}{4}(\lambda_c-\lambda_e). \quad (6)$$

The values of $\frac{f}{4}(\lambda_c-\lambda_e)$ are 0.0034 A, 0.0015 A, and 0.0007 A for the lines H_3 to H_5; applying these corrections we obtain $\bar{\nu}$ for these lines: the values are 23032.5758, 24373.1078, and 25181.3631 for H_3 to H_5, respectively. For all succeeding lines the intensity ratio is unity, and $1/\bar{\nu}$ is identical with λ_0. From equation (3) we get

$$\nu_c=R_H\left\{\frac{1}{2^2}-\frac{1}{M^2}+\frac{\alpha^2}{4}\left(\frac{1}{2^4}-\frac{1}{M^4}\right)-\frac{\alpha^2(M-3)}{3M^4}\right\}$$

$$\nu_e=R_H\left\{\frac{1}{2^2}-\frac{1}{M^2}+\frac{\alpha^2}{4}\left(\frac{1}{2^4}-\frac{1}{M^4}\right)+\alpha^2\left(\frac{1}{2^4}-\frac{M-2}{2M^4}\right)\right\}$$

If we call the expressions in brackets b_c and b_e,

$$\nu=\frac{2\nu_c\nu_e}{\nu_c+\nu_e}=\frac{2R_Hb_cb_e}{b_c+b_e}. \qquad \therefore\ R_H=\frac{(b_c+b_e)\bar{\nu}}{2b_cb_e}. \quad (7)$$

Table II shows the values of R_H obtained by equation (7).

TABLE II

Line	R_H	Line	R_H	Line	R_H
3	109676.844	7	109677.288	11	109677.572
4	6.983	8	7.292	12	7.372
5	6.807	9	7.542		
6	7.241	10	7.673		

The lines 13 to 18 are not known accurately enough to be used in obtaining R_H. The mean of the foregoing values is:

$$R_H = 109677.26 \pm 0.23; \quad \text{and} \quad R_\infty = 109736.45 \pm 0.23,$$

if we use Birge's "best" value $m_0/M_H = 1/1853$.

The variation of R_H is within the limits of experimental error. In future work the lines 6 to 15 will be the point of attack; they can be obtained with reasonably short exposures in the fourth or fifth order, and much better results may be expected.

3. CORRECTIONS TO THEORY

We have seen that Sommerfeld's relativistic quantizing suffices to explain the gross features of observations on the doublet separations of the Balmer lines and on their wave-lengths. Outstanding discrepancies are within the limits of experimental errors in almost all cases, and it seems hopeless to attempt to find out by further experiment whether deviations from theory actually exist.

Another method of attack is available; we can revise the theory to take account of all perturbations which can reasonably be considered as existent, and can examine whether the revised theory agrees with experiment. The alterations mentioned in the introduction to this paper will be discussed in order.

1. The alteration of energy due to asphericity of the nucleus has been treated by Dr. Silberstein.[1] He developed formulae applicable to the most general distribution of charge within the nucleus; the results will be of importance in the theory of heavy atoms with large nuclei. Dr. Silberstein has attempted to explain the fine

[1] *Philosophical Magazine*, **39**, 46, 1919.

structure of the H-lines solely by the assumption of an aspherical nucleus.[1] However, he found that in order to satisfy Curtis' data on the wave-lengths of the first six lines, it is necessary to assume a nucleus whose largest dimension is about 2.10^{-11} cm; when this is done the line patterns for Hα and Hβ do not resemble the observed structures, unless *ad hoc* assumptions as to the intensities of the numerous members are brought in. Without going into details, the theory shows that the spread of the line pattern is reduced in proportion to the square of the nuclear dimensions, other things being equal. The preponderance of evidence is to the effect that the sum of the radii of H-nucleus and electron is not greater than 3.10^{-13} cm; this is about 0.003 of the dimension used by Silberstein; if we adopt this value the width of the line pattern is reduced by the factor 10^{-5} and no observable fine structure would exist. Asphericity of the nucleus cannot cause a shift of any Balmer line by an amount observable spectroscopically; all such shifts from the positions predicted by the simple theory are comprised within the limits of the fine structure. I have carried through the work of showing that asphericity of the electron cannot be detected by observations of the Balmer lines, if the maximum dimension of the electron is less than 3.10^{-13} cm. (In fact this effect could be observed only in very precise measures of the highest frequencies in the X-ray spectra of heavy elements.) The inapplicability of these ideas in the present case does not alter the value of Dr. Silberstein's calculations within their proper domain. Reasoning backward, we may say that since no term arising from asphericity of the ultimate particles is needed to satisfy the data, both nucleus and electron must be very small, if aspherical, or very nearly spherical, if large. This amounts to an independent confirmation of the conclusions drawn from experiments on scattering of alpha and beta particles in light gases.

2. Professor H. A. Wilson[2] has suggested that the potential energy of a hydrogen atom may be regarded as distributed through the space surrounding it, and that this energy will take part to some extent in the motion of the electron. Its presence will modify the motion of the electron, and shifts of spectral lines will result.

[1] *Proceedings of the Royal Society*, A, **98**, 1, 1920.

[2] *Astrophysical Journal*, **56**, 34, 1922.

Roughly, the effect to be expected is a slight narrowing of the fine structure of the H-lines, accompanied by a very small shift. The narrowing is proportional to f, where f is the fraction of $1/2$ of the potential energy which may be considered as moving with the electron. Since these ideas were put forward, Oldenberg's explanation of the narrowing of the doublets has appeared, and seems to leave no room for such a correction. There would be difficulties even if Oldenberg's explanation were left out of account; a readily observable shift of the lines would result if f were as large as 0.2, say, and the fine structure of ionized helium lines would not be like that observed by Paschen.

We shall not raise here the fundamental question whether the energy of an atom in a stationary state is actually spread through the surrounding space or whether this distribution is to be regarded merely as a convenient mathematical artifice, but it is an experimental fact that the motion of the potential energy of the system does not affect its total energy by an observable amount.

3. We shall calculate the correction due to a nuclear magnetic moment. In 1915, H. S. Allen[1] carried through a similar analysis for the circular orbits of hydrogenic atoms. We neglect the relativity correction and the motion of the nucleus, and attribute to the nucleus an intrinsic magnetic moment, M. If we suppose the electron has a magnetic moment of the same order of magnitude as M, a correction arises which is of the magnitude $(m_0/M_H)^3$ compared to that due to the nuclear moment; this is negligible. Likewise, we may neglect the reaction on the nucleus due to the fact that it is exerting force on the electron. Let us take the nucleus as the origin of a polar co-ordinate system, r, θ, ϕ; θ is measured in the plane defined by the nucleus and the tangent to the electronic orbit at any convenient initial time. It will be found that the orbital plane is invariable in position, so ϕ is always $\pi/2$. The electrical potential energy is $-Ee/r$ where E is the nuclear charge. We now calculate the magnetic energy. The magnetic field due to an electron moving with velocity v in a direction (α, β, γ), is in Gauss,

$$H = \frac{ev \sin \psi}{cr^2}, \tag{8}$$

[1] *Philosophical Magazine*, **29**, 40 and 714, 1915.

at a distance r from the electron, if ψ be the angle between its direction of motion and the radius vector drawn to the point of evaluation of H. H is perpendicular to the radius vector and the direction (α, β, γ); we call its direction cosines l', m', $n.'$ The potential energy associated with the moment M, having direction cosines l, m, n, in the field H, is, in electromagnetic units,

$$V_M = -MH(ll'+mm'+nn'). \tag{9}$$

We can now write down Lagrangian equations; only the equations for the co-ordinates l and m are needed. If T and V be the kinetic and potential energies of the system we have

$$\frac{d}{dt}\left(\frac{\partial(T-V)}{\partial \dot{l}}\right)-\frac{\partial(T-V)}{\partial l}=0; \qquad \frac{d}{dt}\left(\frac{\partial(T-V)}{\partial \dot{m}}\right)-\frac{\partial(T-V)}{\partial m}=0. \tag{10}$$

These equations reduce to the conditions for equilibrium of the nucleus,

$$\frac{\partial V}{\partial l}=0; \qquad \frac{\partial V}{\partial m}=0. \tag{10'}$$

These equations are an expression of the tacit assumption that since the nucleus is so small and so massive, we may neglect its kinetic energy of translation and of rotation, and that under these assumed conditions it will orient itself permanently in a configuration satisfying the equilibrium-equations. V_M may be written

$$-MH(ll'+mm'+\sqrt{1-l^2-m^2}\cdot n')$$

and equations (10′) become

$$l'-\frac{n'l}{\sqrt{1-l^2-m^2}}=0; \qquad m'-\frac{n'm}{\sqrt{1-l^2-m^2}}=0, \tag{10''}$$

and finally, by symmetry, we obtain the equations,

$$l : m : n = l' : m' : n'. \tag{10'''}$$

The axis of the magnetic moment is always normal to the instantaneous orbital plane. The force on the electron is always in the plane of its orbit and $\phi = \pi/2$ always; the problem is two dimensional. Only one of the two possible orientations of the nucleus gives stable equilibrium. We suppose this to be the position actually occupied. Then

$$V_M = -MH = -\frac{Mev \sin \psi}{cr};$$

$v \sin \psi$ is the component of the velocity of the electron perpendicular to the radius vector, which is $r\dot{\theta}$; therefore,

$$V = -\frac{Me\dot{\theta}}{cr}. \tag{11}$$

Let us call W the total energy of the atom in a conservative state.

$$W = \frac{1}{2m_0}\left[(m_0\dot{r})^2 + \frac{1}{r^2}(m_0 r^2\dot{\theta})^2\right] - \frac{Ee}{r} - \frac{Me\dot{\theta}}{cr}. \tag{12}$$

Since the magnetic force on the electron due to the nuclear moment is always directed along the radius vector, the angular momentum is constant; we apply the quantum condition,

$$p = m_0 r^2\dot{\theta} = nh/2\pi \tag{13}$$

and $Me\,\dot{\theta}/rc$ becomes $nhMe/\,2\pi m_0\, r^3\, c$. Equation (12) becomes

$$\frac{1}{2m_0}\left[(m_0\dot{r})^2 + \frac{p^2}{r^2}\right] - \frac{eE}{r} - \frac{nh\,Me}{2\pi m_0 r^3 c} = W$$

or,

$$(m_0\dot{r})^2 = 2m_0 W + \frac{2m_0 eE}{r} - \frac{p^2}{r^2} + \frac{nh\,Me}{\pi c}\,\frac{1}{r^3}.$$

Put $A = 2m_0\, W$, $B = m_0\, eE$, $C = -p,^2$ $D_1 = nh\,Me/\pi c$; the quantum condition for the co-ordinate r is

$$J_4 = \int m_0\dot{r}\, dr = \int \sqrt{A + \frac{2B}{r} + \frac{C}{r^2} + \frac{D_1}{r^3}} \cdot dr = n'h. \tag{14}$$

The integral is extended over a complete cycle of values of r, and is given on page 479 of the second edition of Sommerfeld's *Atombau* (p. 670 of the 3rd. ed.):

$$J_4 = -2\pi i\left(\sqrt{C} - \frac{B}{\sqrt{A}} - \frac{BD_1}{2C\sqrt{C}}\right)$$

where we are to use the negative value of $\sqrt{C}$, i.e., $-inh/2\pi$. Finally

$$J_4 = n'h = -nh + \frac{2\pi i m_0 eE}{\sqrt{2m_0 W}} + \frac{8\pi^3 m_0 e^2 EM}{cn^2 h^2}. \qquad (15)$$

We shall call the last term on the right hP and shall write $E = Ze$, so that

$$P = \frac{8\pi^3 m_0 e^3 ZM}{cn^2 h^3}, \qquad (16)$$

$$W = \frac{-2\pi^2 m_0 e^4 Z^2}{h^2(n+n'-P)^2} = \frac{-hcRZ^2}{(n+n')^2}\left[1 + \frac{2P}{(n+n')} + \ldots\right]. \qquad (17)$$

The magnetic correction to the wave number of any spectrum line will be

$$RZ^2 B \cdot \left(\frac{1}{n^2(n+n')^3} - \frac{1}{m^2(m+m')^3}\right) \qquad (18)$$

where B is defined as $2Pn^2$. If ρ be the number of Weiss magnetons equivalent to the nuclear moment we have

$$M = \rho \times 1.854 \quad 10^{-21}. \qquad \text{(Electromagnetic units.)} \qquad (19)$$

$$RB = \rho Z \times 109736 \times 1.071 \times 10^{-5} = 1.175\, \rho Z. \qquad (20)$$

A large amount of evidence could now be adduced for the non-existence of a nuclear moment as large as one Weiss magneton; we content ourselves with computing the magnetic shifts for the allowed components of Hα, on the basis of a single Weiss magneton:

Transition	Shift
(3,0) to (2,0)	−.013 A
(1,2) to (2,0)	+.003 A
(2,1) to (1,1)	−.055 A

Thus the two main components of Hα approach each other by the amount 0.043 A, which is far greater than the narrowing of the doublet usually observed. The relations are quite similar for succeeding lines, and for lines of the 3-quantum series of ionized helium; in all these cases the fine structure will be distorted by a readily observable amount.

The conclusion is that the hydrogen nucleus and the alpha particle cannot possess intrinsic moments as large as one Weiss magneton, and were there any object in so doing, we could set a still smaller limit to the magnitude. In order to prove this fact directly, it would be necessary to perform the Stern and Gerlach experiment for H-nuclei and alpha particles.[1] The shifts predicted by this theory for lines in the K series of an element of atomic number Z are of the order of magnitude $\rho/Z \times 0.013$ A, which is observable in light elements if ρ is as large as 5; but this effect cannot be separated from other perturbations of much greater size.

I wish to express my thanks to Professor R. W. Wood for the use of his spectrum plates and his advice in connection with their measurement; to Mr. B. Kurrelmeyer for his generous aid in checking calculations; and to Professors Ames, Pfund, and Wood, and Drs. F. L. Mohler, A. Q. Tool, and P. D. Foote, who have kindly given the paper the benefit of their criticism.

JOHNS HOPKINS UNIVERSITY
December 10, 1922

[1] *Zeit. f. Phys.*, **9**, 349, 1922.

WAVE-LENGTH STANDARDS IN THE EXTREME ULTRA-VIOLET

By J. J. HOPFIELD and S. W. LEIFSON

ABSTRACT

Extreme ultra-violet spectra of hydrogen, oxygen, nitrogen, helium, and air.—The wave-lengths of 37 strong lines *between* λ 800 *and* λ 1800 occurring in condensed discharge spectra of impure hydrogen, oxygen, nitrogen, helium, and air are determined, with a probable error of less than 0.1 A, from photographs, on specially prepared ultra-violet films, taken with a Rowland concave grating having a radius of curvature of 50 cm.

INTRODUCTION

In the extreme ultra-violet spectra of impure hydrogen, oxygen, nitrogen, helium, and air obtained with a condensed discharge, there occur a number of strong lines which may serve as standards, since they are almost always present. Several observers have published tables of wave-lengths between λ 800 and λ 1800, but their measurements have perhaps only in a very few cases yielded results accurate to 0.1 A. In view of the growing interest in this part of the spectrum and its importance in atomic theory a careful determination has been made of the wave-lengths of a number of easily obtained characteristic lines to serve as standards in the region λ 800 to λ 1800. These, together with some additional lines known accurately from theory, may serve not only as reference standards for interpolation in this region, but also as an aid to establishing other standards in the region λ 300 to λ 800, a region now accessible to spectroscopists. The wave-lengths are expressed in I.A. in vacuum, since both the comparison and the measured spectra were obtained in a vacuum. The standard wave-lengths used were in I.A. reduced to vacuum.

METHOD

From a large number of photographs of the ultra-violet spectra of hydrogen, oxygen, and nitrogen about twenty-five of the best were selected for measurement. These photographs, recorded on specially prepared ultra-violet films, were made with a Rowland concave grating having a radius of curvature of 50 cm. The photo-

graphs cover a range from 0 to 5000 A, and they therefore contain the second, third, and fourth orders of lines whose wave-lengths lie between λ 800 and λ 1800. By making enlarged prints of each film to be measured, the higher orders were easily recognized and marked. A superimposed mercury arc spectrum, giving about twenty distinct lines between λ 2400 and λ 4800, furnished standards. Stiles's values for the mercury arc lines[1] were used, and the wave-lengths were reduced to vacuum by means of the *Bureau of Standards* tables.[2]

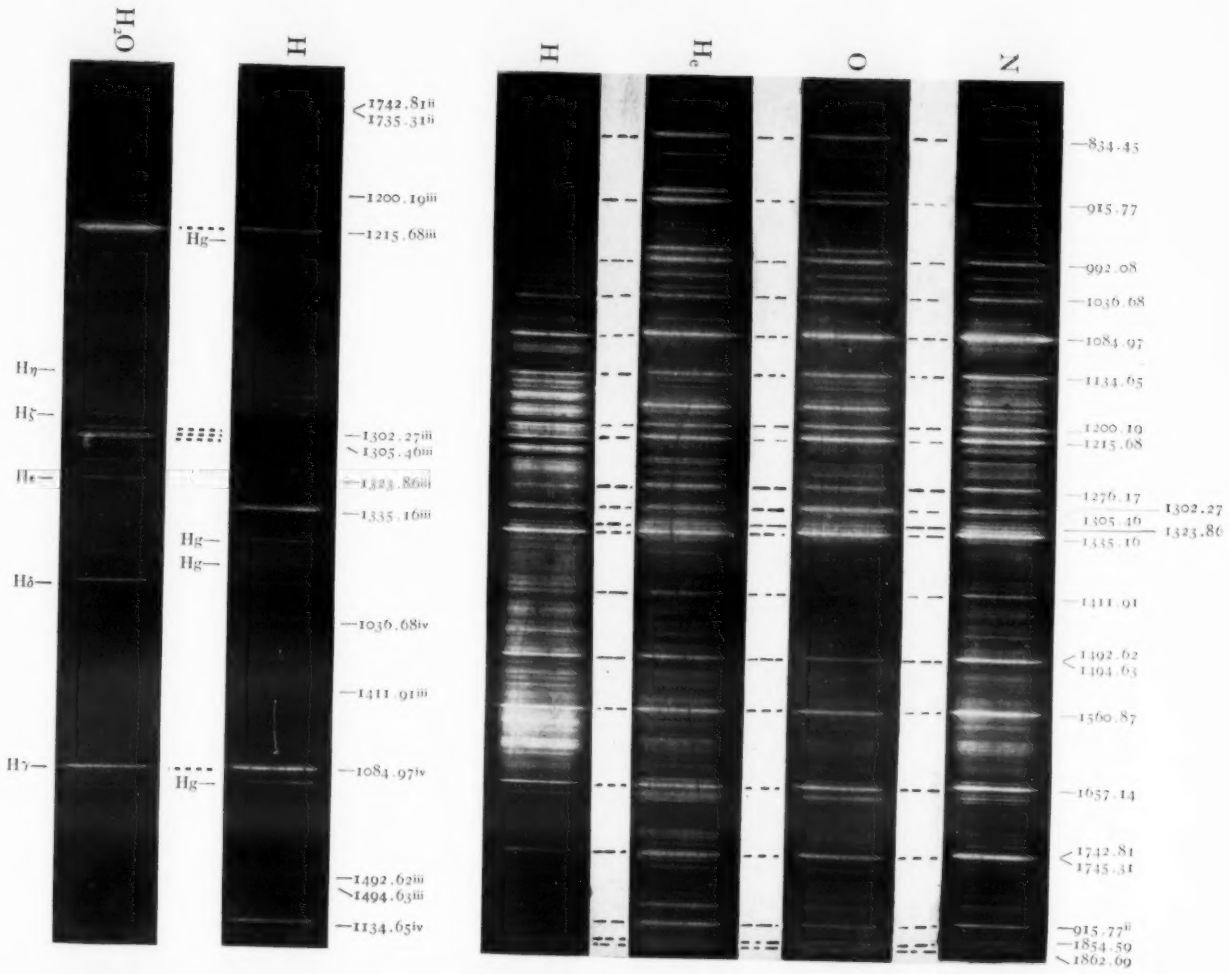
The positions of the lines were measured with a 20-cm Gaertner comparator, owned by the Rumford Committee of the American Academy of Sciences, and kindly loaned to the authors by Professor R. T. Birge. The wave-lengths of the unknown lines were obtained by direct interpolation between two standard lines. Since the photographs were made with the gas in the spectrograph under a pressure of 0.2 mm or less, no correction for dispersion of the medium was made.

Most of the lines were measured in the third order, and in a few cases also in the second and fourth orders. On each of the several films, ten settings of the micrometer were made on each line. The average deviation from the average in ten settings on a line was usually less than 0.005 mm, hence, as calculated from the dispersion of the grating, which is approximately 34 A per mm, the corresponding deviation in the wave-length determination was 0.17 A in the first order and proportionately less in the higher orders. The error from this source would thus average about 0.06 A. The only other source of error that needs to be considered is the possibility of a shifting of the comparison spectrum with respect to the unknown spectrum, owing, first, to asymmetrical illumination of the grating with the mercury arc, and second to shrinkage of the film in the interval between two exposures. Some photographs which showed evidence of a shift were rejected. In the case of most of the films measured, several known lines, such as Hγ and Hδ, were included among the lines measured, and if the wave-lengths computed for these lines in the first order differed by more than 0.2 A from the

[1] *Astrophysical Journal*, **30**, 48, 1909.

[2] *Bureau of Standards Bulletin*, **14**, 731, 1919.

PLATE IV


O'H
H
H
He
O
N
1742.81iii
1735.31iii
1200.19iii
1215.68iii
Hη
Hζ
Hε
Hδ
Hγ
Hg
1302.27iii
1305.46iii
1323.86iii
1335.16iii
Hg
Hg
1036.68iv
1411.91iii
1084.97iv
Hg
1492.62iii
1494.63iii
1134.65iv
834.45
915.77
992.08
1036.68
1084.97
1134.65
1200.19
1215.68
1270.17
1302.27
1305.46
1323.86
1335.16
1411.91
1492.62
1494.63
1560.87
1657.14
1742.81
1745.31
915.77ii
1854.59
1862.69

correct values, the film was rejected. Care was also taken to measure standard lines along with the unknown lines as a further check on the results. After all the films had been measured once, they were measured a second time after an interval of several months.

RESULTS

The illustrations show how the lines whose wave-lengths have been determined appear in the first order. The two sharp lines at λ 1854.59 and λ 1862.69 are well-known aluminium lines whose wave-lengths have been accurately determined by Eder.[1] They show clearly on most of our photographs.

The higher orders are indicated by Roman numeral exponents, and some of the hydrogen Balmer series lines are also shown.

The wave-lengths in the table are probably accurate to within the ranges signified by A, B, and C, respectively: A indicating a probable error in wave-length of ±0.05 A or less; B, ±0.10 A or less; C, ±0.15 A or less.

The measured wave-lengths are the averages of 80 to 150 determinations obtained from as many as 8 to 15 films, respectively. The value obtained for the resonance line of hydrogen, 1215.68 A, which is the average of 150 determinations, agrees very well with the theoretical value, 1215.67 A, the value found experimentally also by the senior author.[2] The wave-lengths of five additional lines of the Lyman series, of which the last three were recently found by one of the authors,[3] are likewise given in the table. Theoretical values in vacuum are used.

The group of three lines, an oxygen triplet, at λ 1302.27, λ 1304.96, and λ 1306.12, was measured on twelve different photographs in the third order, using Curtis' values[4] for Hδ and Hη as standards. Spectrum 6 on the plate of illustrations is a part of the spectrum obtained with water vapor under very low pressure. It shows clearly the third orders of the first line of the Lyman series and the oxygen triplet mentioned above, besides five members,

[1] *Zeit. für Wiss. Phot.*, **14**, 144, 1914.

[2] Hopfield, *The Physical Review* (Series II), **20**, 573, 1922.

[3] Hopfield, *Nature*, **110**, 732, 1922.

[4] *Proceedings of the Royal Society of London*, A, **90**, 605, 1914.

TABLE I

Present Work				Lyman*	Millikan, Bowen, and Sawyer†	McLennan and Petrie‡
λ Measured	Intensity	λ of Center of Gravity Computed	Accuracy			
833.35	3					
834.53	5	834.45	B			
835.28	4					
915.59	3					
916.03	2	915.77	A			
991.57	2					
992.42	3	992.08	A			
1036.33	2					
1037.03	2	1036.68	A	1037.0	1036.7	1036.8
1083.97	2					
1084.52	3					
1085.64	5	1084.97	A	1084.9	1085.3	1085.2
1134.31	4					
1135.00	4	1134.65	A	1134.7		1134.7
1199.56	3					
1200.25	3					
1200.76	3	1200.19	B	1199.8		1199.7
1215.68	10	1215.68	A	1216.0		1215.8
1275.08	3					
1276.22	4					
1277.19	3	1276.17	C			
1302.27	6	1302.27	A	1302.5		1302.9
1304.96	4					
1306.12	3	1305.46	A			
1323.86	2	1323.86	B	1323.4	1323.7	
1334.57	5					
1335.75	5	1335.16	B		1335.0	1334.8
1411.91	2	1411.91	B			1411.6
1492.62	3	1492.62	B			1492.3
1494.63	3	1494.63	B			1494.4
1560.46	5					
1561.39	4	1560.87	B		1561.3	1560.8
1656.33	3					
1657.08	4					
1658.04	3	1657.14	C		1657.6	1656.8
1742.81	5	1742.81	B	1742.7		1742.6
1745.31	5	1745.31	B	1745.3		1744.9

FIVE THEORETICAL VALUES

1215.67	972.54	937.81
1025.73	949.75	930.76

* *Astrophysical Journal*, **43**, 89, 1916.

† *Ibid.*, **53**, 150, 1921.

‡ *Transactions of the Royal Society of Canada* Sec. III, 1921.

the third to the seventh, respectively, of the Balmer series in the first order. $H\epsilon$ and $H\zeta$ were measured along with the three members of the oxygen triplet. The former differed by an average of 0.03 and 0.04 A, respectively, from the correct values. The average deviation from the mean values for each member of the triplet was 0.03 A. Hence it seems legitimate to claim an accuracy of 0.03 A for these lines.

Since many of the complex lines are resolved for the first time in the higher orders shown on our films, and since they are not ordinarily resolved in the first order with a grating having a focal length of 100 cm or less, their centers of gravity have been calculated, based on the estimated intensity of the members. The groups at λ 915.77, λ 1134.65, and λ 1657.14 are probably even more complex than indicated in the table. The highest orders of λ 915.77 and λ 1134.65 observed indicate that they are composed of three lines. The sixth order of λ 834.45 shows no fewer than five lines. The position of the center of gravity is based on the entire group, of which only the strongest lines are shown in the table.

The similarity of the first three spectra on the plate of illustrations shows that these spectra are probably air spectra with admixture of nitrogen, oxygen, and helium, respectively. They are easily produced by air alone and thus form convenient comparison spectra for this region.

Since the wave-lengths given are believed to be more accurate than any previously published for this region of the spectrum, and since the lines are all easily obtained with a condensed discharge at low pressures, especially in air, it is thought that the results may be of use to other spectroscopists working in the extreme ultra-violet.

DEPARTMENT OF PHYSICS
UNIVERSITY OF CALIFORNIA
February 1923

NOTICE TO CONTRIBUTORS

There is occasionally published in the *Astrophysical Journal* a Standing Notice (for instance, on pages 179–80 of the number for September 1917). This is principally intended to guide contributors regarding the manuscript, illustrations, and reprints. This notice contains the following paragraph:

> Where unusual expense is involved in the publication of an article, on account of length, tabular matter, or illustrations, arrangements are made whereby the expense is shared by the author or by the institution which he represents, according to a uniform system.

The present sheet has been printed for amplifying further that paragraph.

The "uniform system" according to which "arrangements are made" is as follows: The cost of composition in excess of $50, and of stock, presswork, and binding of pages in excess of 40 pages, for any one article shall be paid by the author or by the institution which he represents at the current rates of the University of Chicago Press. When four articles from one institution or author have appeared in any one volume, on which the cost of composition has amounted to $50 each, or when the total cost of composition incurred by the *Astrophysical Journal* on articles for one institution has reached the sum of $200, the entire cost of the composition, stock, presswork, and binding of any additional articles appearing in that volume shall be paid by the author or by the institution which he represents.

As to illustrations, the arrangement cannot be quite as specific, but it may be generally assumed that not more than three half-tone inserts can be allowed without payment by the author. The cost of paper, presswork, and binding for each full-page insert is about $8.00, aside from the cost of the half-tone itself. In the matter of zinc etchings, considerable latitude has to be allowed, as in many cases diagrams take the place of more expensive tables. It may be assumed, however, that it will seldom be possible for the *Journal* to bear an expense of over $25 for diagrams and text illustrations in any one article.

Contributors should notice that since January, 1917, it has been impossible to supply any free reprints of articles.

Reprints of articles, with or without covers, will be supplied to authors at cost. No reprints can be furnished unless a request for them is received before the *Journal* goes to press.

Every article in the *Astrophysical Journal*, however short, is to be preceded by an abstract prepared by the author and submitted by him with the manuscript. The abstract is intended to serve as an aid to the reader by furnishing an index and brief summary or preliminary survey of the contents of the article; it should also be suitable for reprinting in an abstract journal so as to make a reabstracting of the article unnecessary. For details concerning the preparation of abstracts, see page 231 in the April, 1920, number of the *Journal*.

THE EDITORS